Astrophysics and Fusion Plasmas: application of the SparSpec algorithm to the data analysis and design of the ITER high-frequency Mirnov coil diagnostic system

D.Testa

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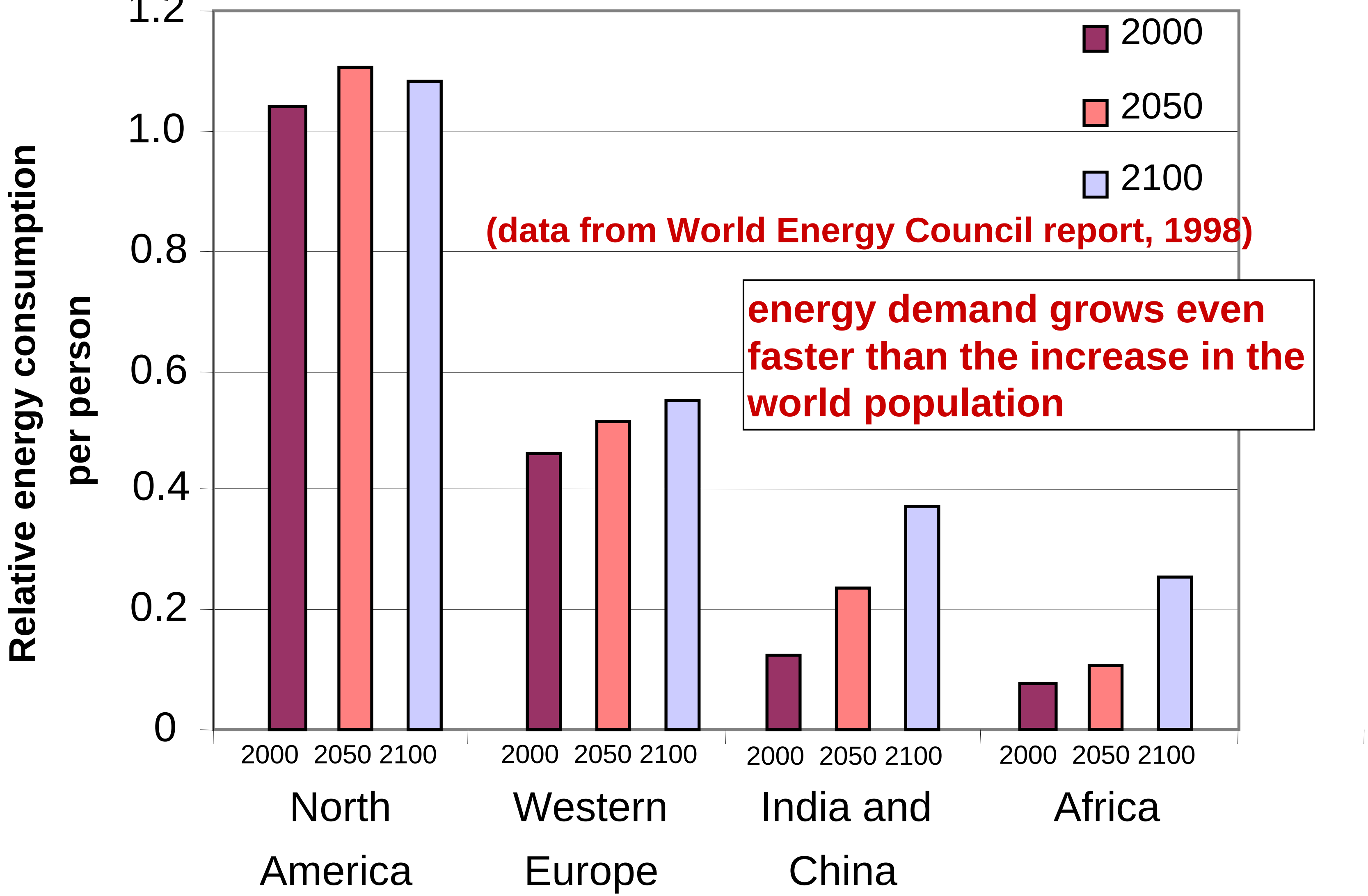
Topical Overview

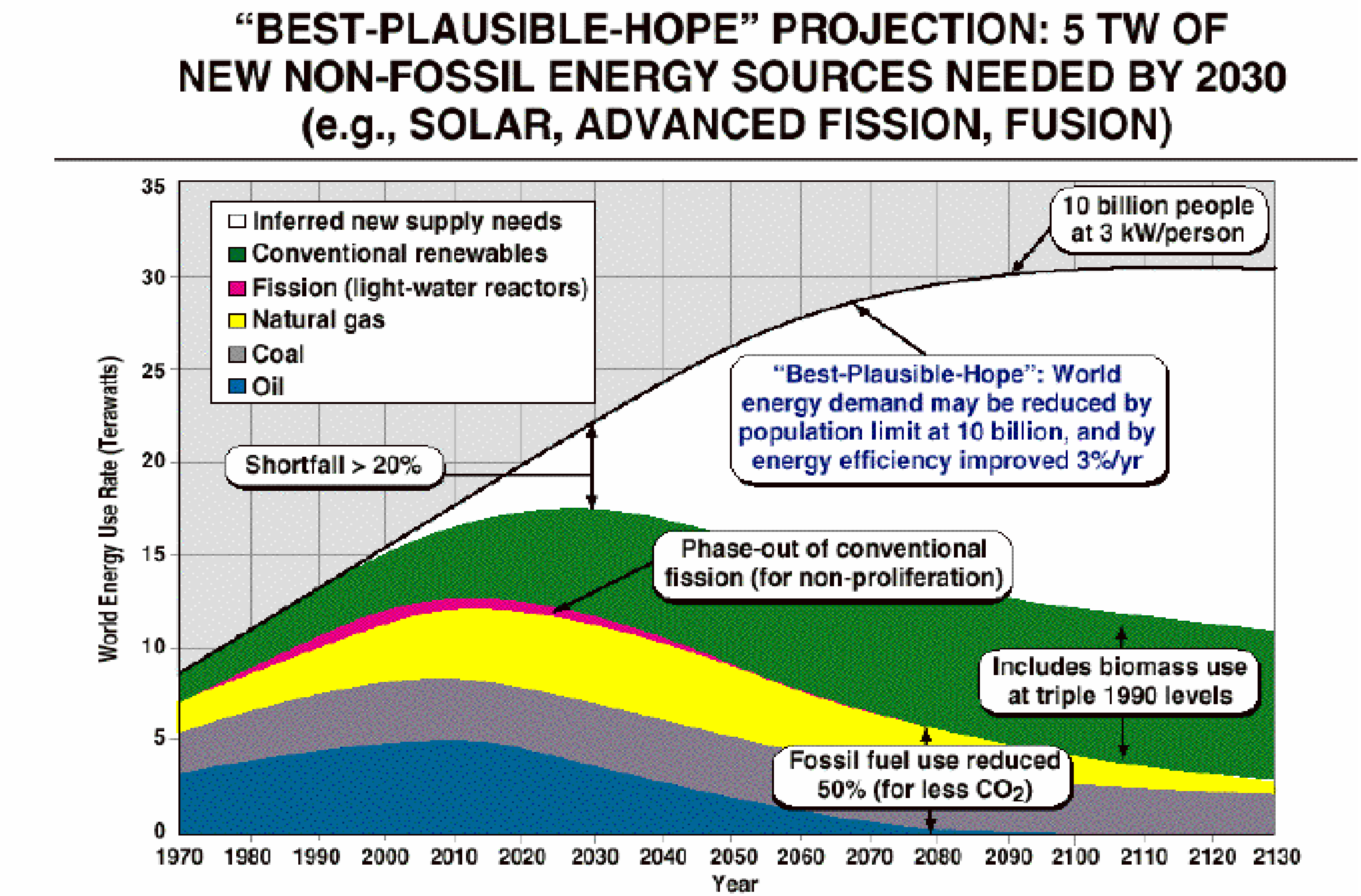
- **introduction: world's energy needs and the role of fusion**
- **the problem: measurement of the mode numbers of the magnetic instabilities in tokamaks**
  - fusion plasmas and tokamaks - JET
  - magnetic instabilities in tokamaks
  - **why we need to know the mode numbers of the magnetic instabilities**
- **the solution: various analysis methods to determine the toroidal and poloidal mode numbers**
  - linear phase fitting, Fourier decomposition, Wigner and Choi-Williams distributions, wavelets and SVD, ...
  - the sparse representation of signals and the SparSpec code
  - **why SparSpec is best for our applications: real-time analysis on JET**
- **the application: baseline design and system optimization of the high-frequency magnetics diagnostic in ITER**
  - fusion plasmas and tokamaks – ITER
  - the baseline design for the high-frequency magnetics diagnostic in ITER
  - **system optimization: putting together tools from astronomy and fusion plasma**

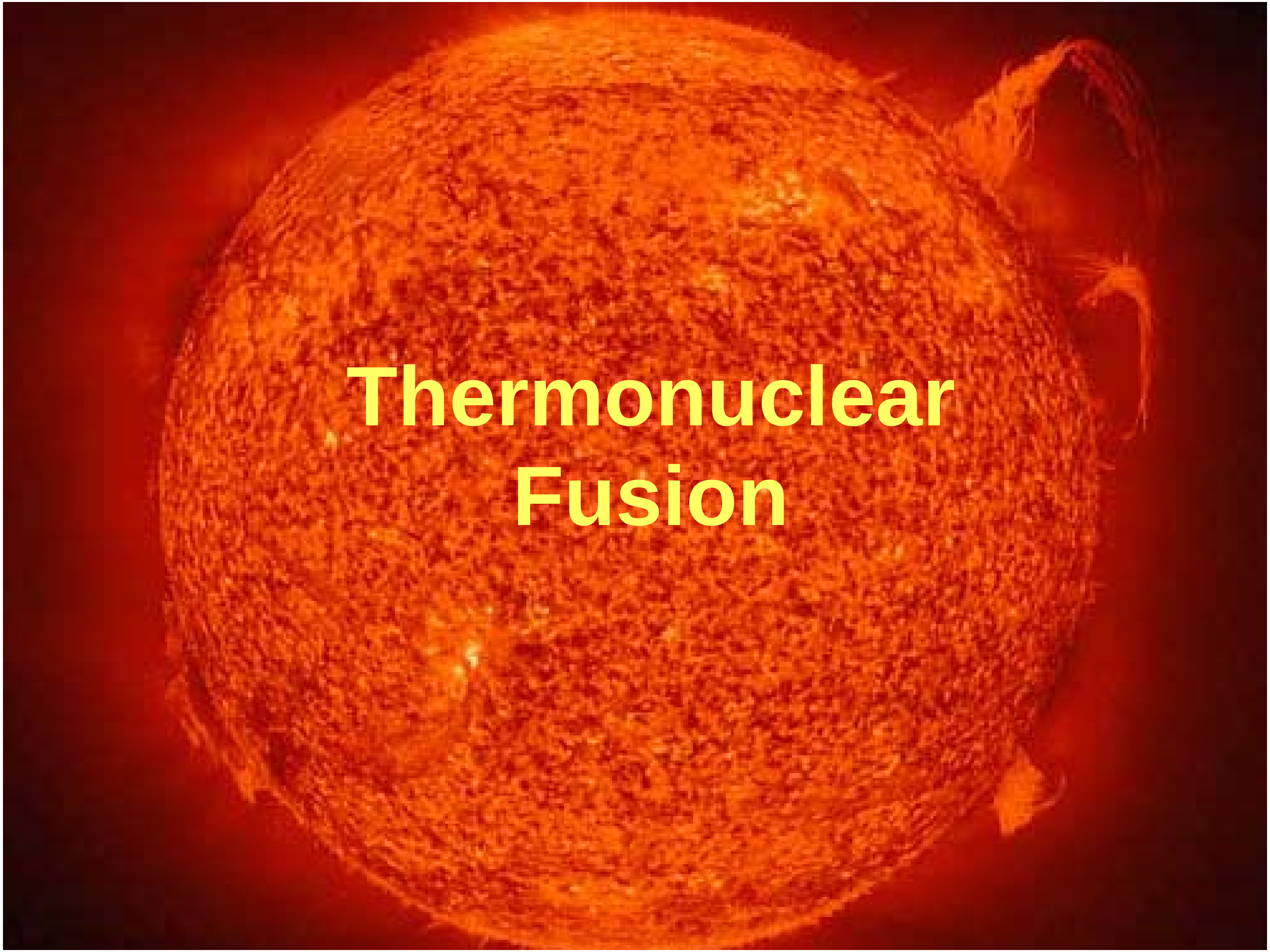
Pro-Capita Energy Consumption: Year 2000, 2050 and 2100

IIASA/WEC 1998: “business as usual” scenario



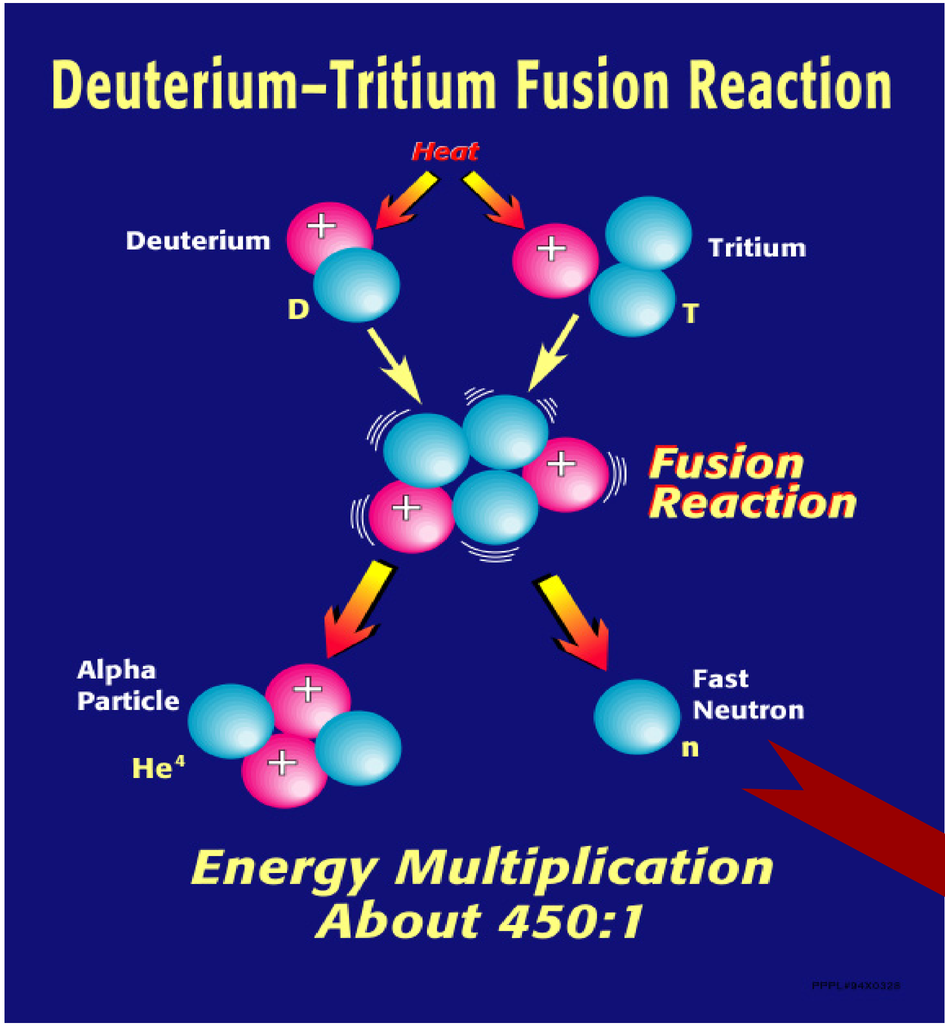
Scarcity of Resources Related to Limitations on CO_2 Emissions




Thermonuclear
Fusion

Fusion Reactions for Energy Production

$$D+T \rightarrow {}^{4}He\,(3.5MeV) + n(14MeV)$$



tritium replenishment

Li

$n+Li^{6(7)} \rightarrow He^{4}+T\ (+n)$

plasma self-heating

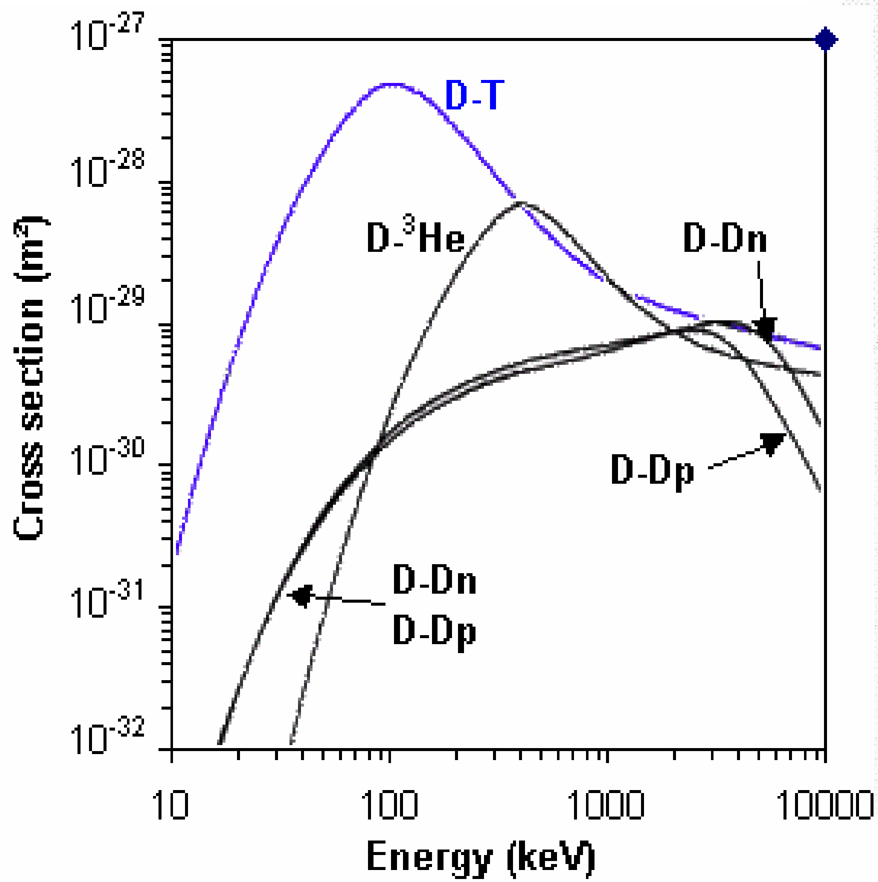
energy for electricity

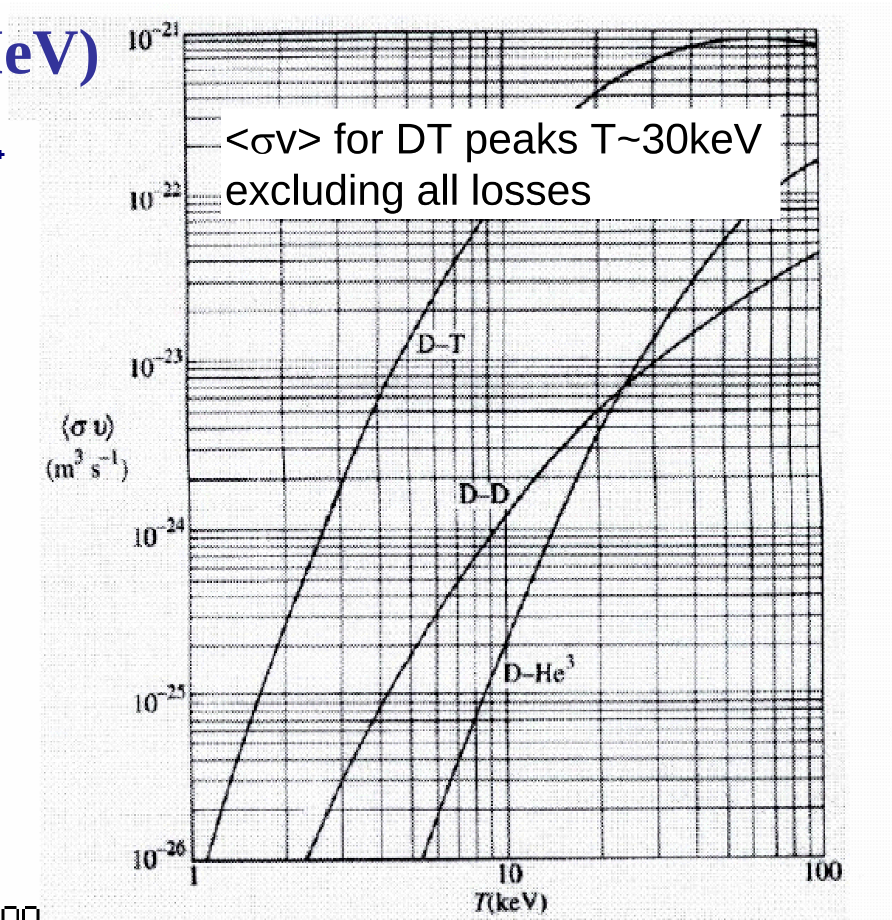
Advantages of Fusion Energy

- high energy density fuel
  - 1g D-T →26'000kW-hr (1g coal→0.003kW-hr)
- abundant fuel, available everywhere
  - D is 1/6500 of H (OK for >10^{10} years)
  - Li is 17ppm of crustal rock (OK for >10^3 years)
    - *lithium is used for tritium breeding inside the fusion reactor*
- **minimum environmental impact**
  - no CO_2 emission
  - **no long-lived, high-level radioactive waste: nuclear activation is similar to that of a modern coal plant ~20 years after shutdown**
- **no risk of nuclear accidents**
  - always <5min of fuel at any one time in a fusion reactor
- **no generation of weapon-grade material**
- geographically concentrated, very little use of land
- not subject to local or seasonal variations

Fusion Reactions for Energy Production in a Fusion Power Plant: We Need to Make a Plasma!

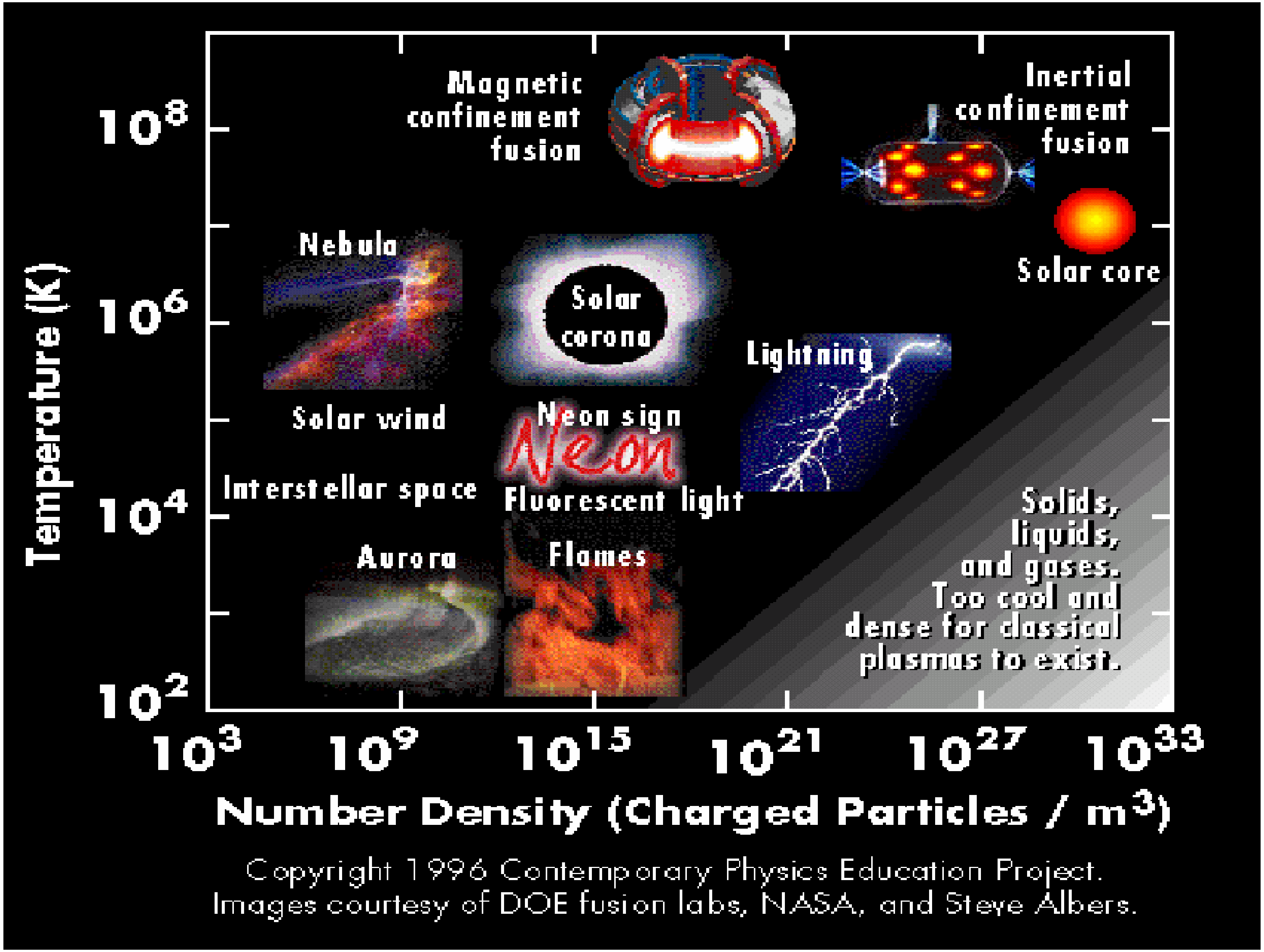
D+T → ^{4}He (3.5MeV) + n(14MeV)



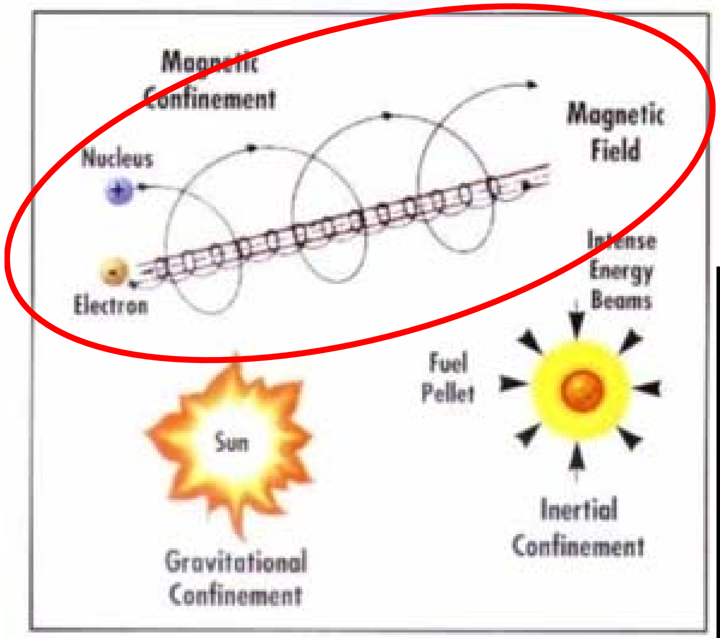


fusion cross-section averaged over particles' distribution function

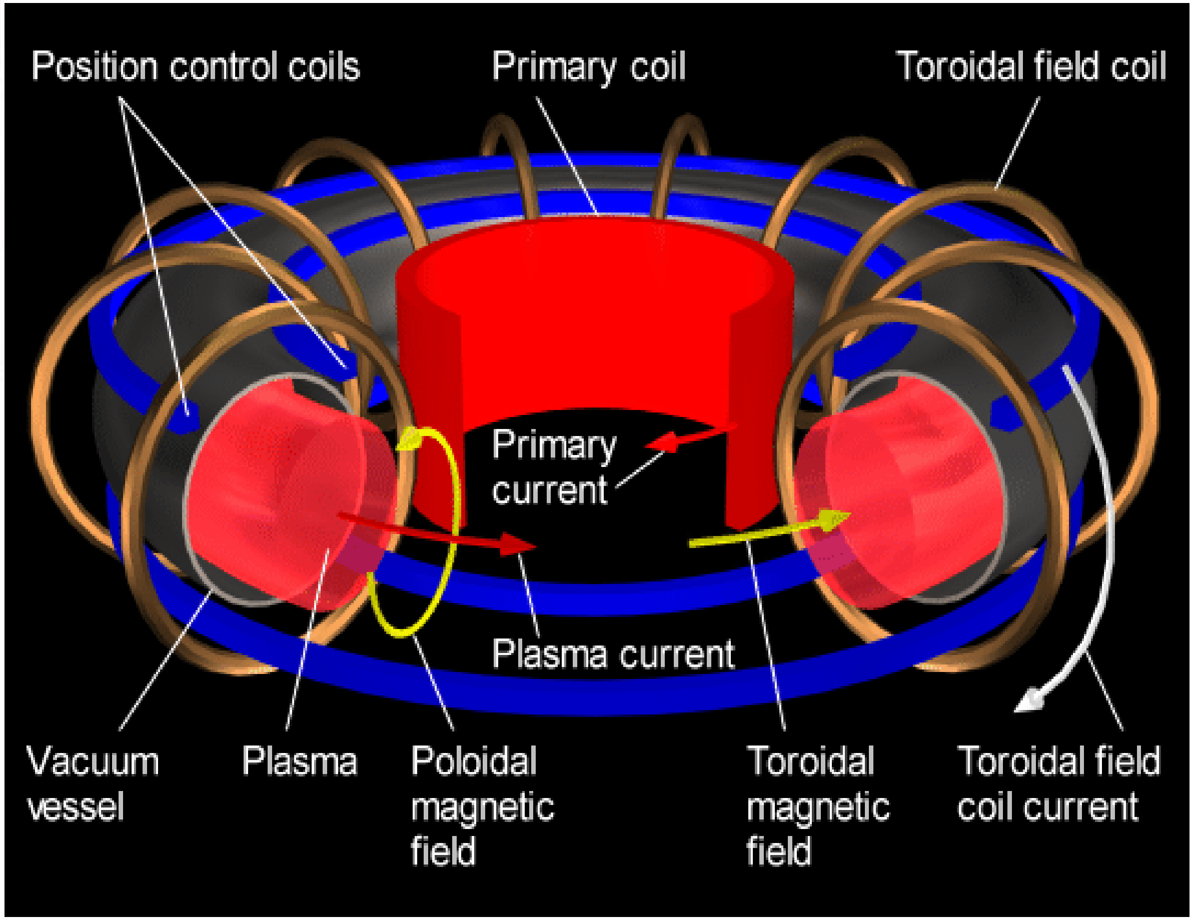
Examples of Plasmas in Nature



Plasma Confinement by Magnetic Fields



the tokamak concept



Magnetic Confinement

- $n \sim 10^{20} m^{-3}$
- $\tau_E \sim 10 sec$
- $T_i \sim T_e \sim 10 keV$
- $\lambda_{MFP} \sim 10^8 m$

Fusion Energy Production: the Lawson Criterion

- for fusion to occur, a plasma must be confined for long enough at the required values of density and temperature
  - need to achieve a sufficiently high value for the triple product:
    density × temperature × energy confinement time = $n \times T \times \tau_E$
- **fusion power density ≡ P_{FUS} $= n_D n_T \langle\sigma v\rangle E_f$; $E_f = 17.6\,\mathrm{MeV}$**
  $= \frac{1}{4} n^2 \langle\sigma v\rangle E_f$; ($n_D = n_T = n/2$)
- **of this, 20% is in the α's: $P_\alpha = P_{FUS}/5$**
- **definition of fusion gain $Q = P_{FUS}/P_{heat}$**
- to achieve P_{FUS} ~1GW we **must confine** a plasma for a sufficiently long time over a volume >$10\,\mathrm{m}^3$
  - example: $n = 5\times10^{20}\,\mathrm{m}^{-3}$, $T = 20\,\mathrm{keV} \sim \max(\langle\sigma v\rangle)$, $\tau_E = 10\,\mathrm{sec}$
- *this is not as easy as it may sound ...*

The Lawson Criterion: Energy Losses

- **breakeven: Q=1 ➔** to sustain the fusion reaction, energy losses are balanced by power reinjected via external heating
- **ignition: Q $\geq$5 ➔** if α's are confined, external heating is no more needed and the **fusion reaction is sustained by the self-heating from the α's themselves**
  – *onset of the burning plasma regime*
  – *this is the operational regime foreseen for a fusion power plant*

- **what can deteriorate the energy confinement time?**

- **what can deteriorate the alpha particles confinement?**

Needs for Burning Plasma Studies

- capability of generating and measuring fusion α's (or other equivalent fast ions) with similar energies (>1MeV)
- plasma size, I_p, B_T sufficient to confine these particles in reactor relevant regimes (density, temperature, τ_E)
  - maximum Q achievable in JET: Q~0.95 (transient)
  - *need steady state Q≥5 for ignition ➔ ITER*

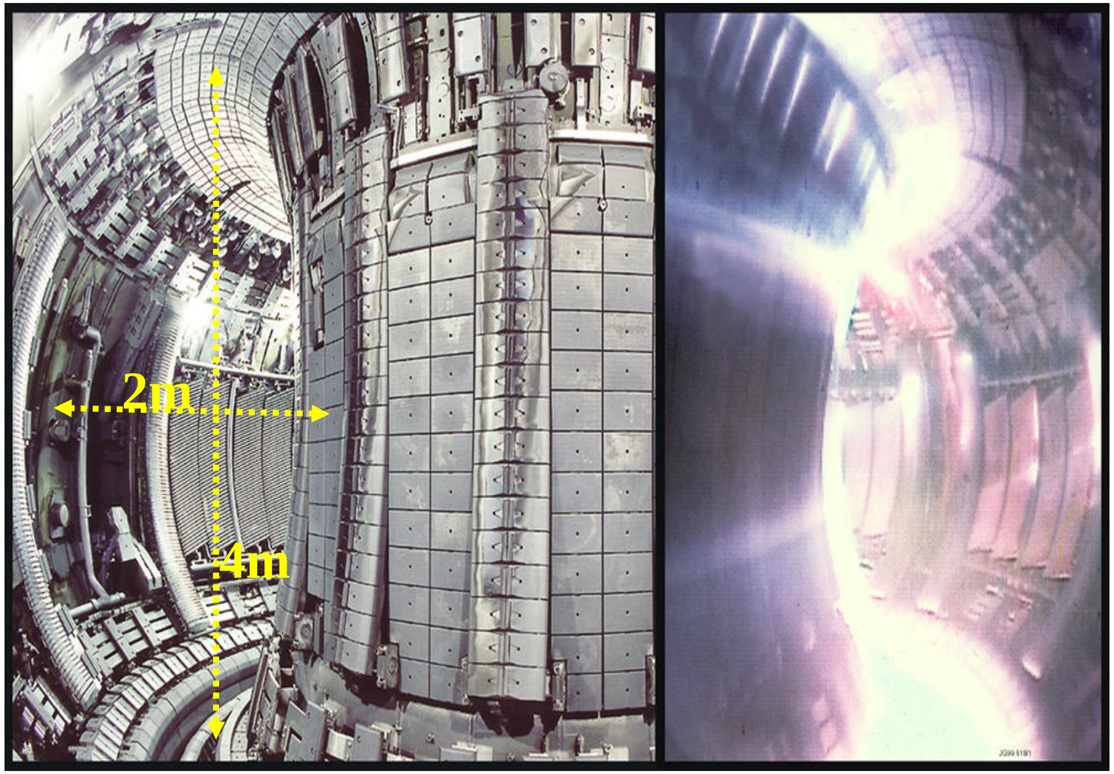
the JET tokamak

R~3m; max B_T~4T; max I_p~4MA

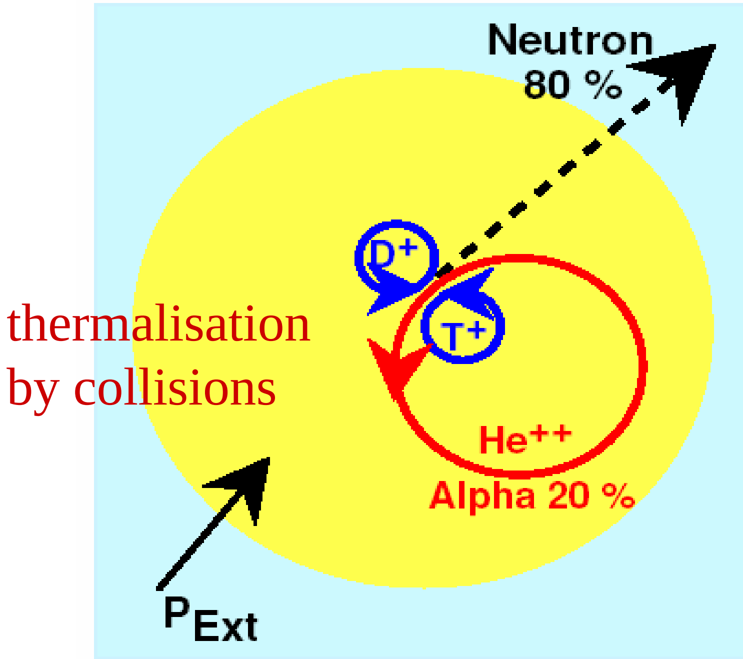
D, H, He and D-T plasmas

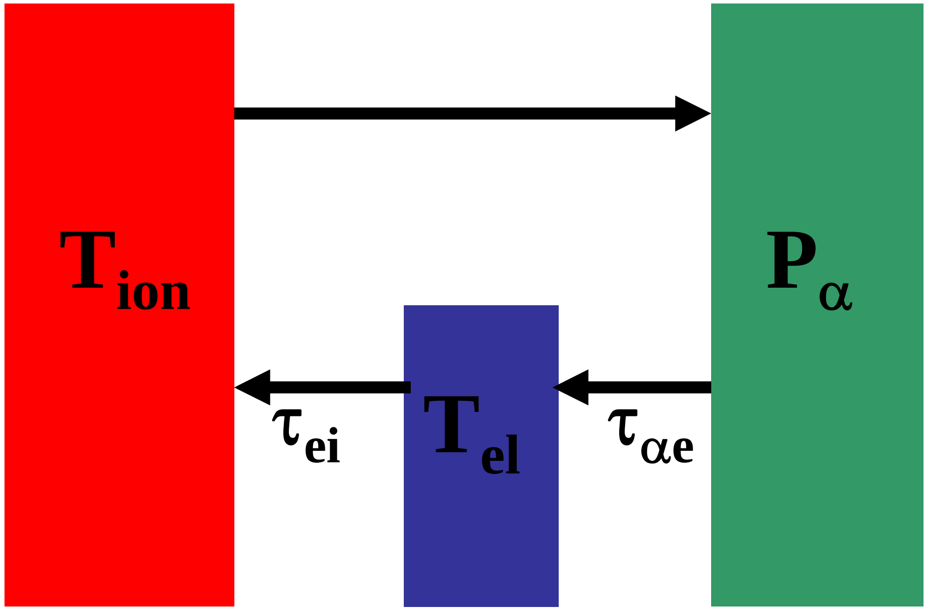
maximum P_{FUS}=16MW, Q~0.7

need ITER to achieve Q≥5



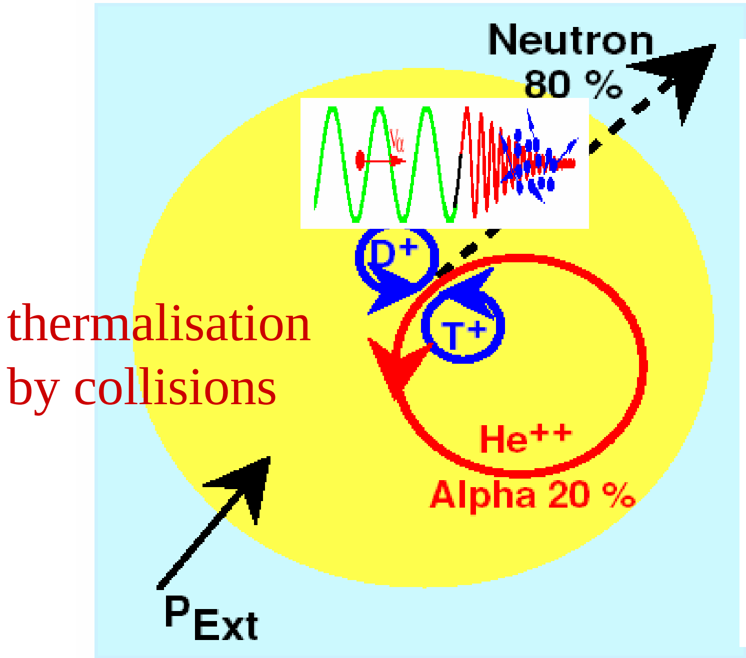
Burning Plasma: the Self-Heating

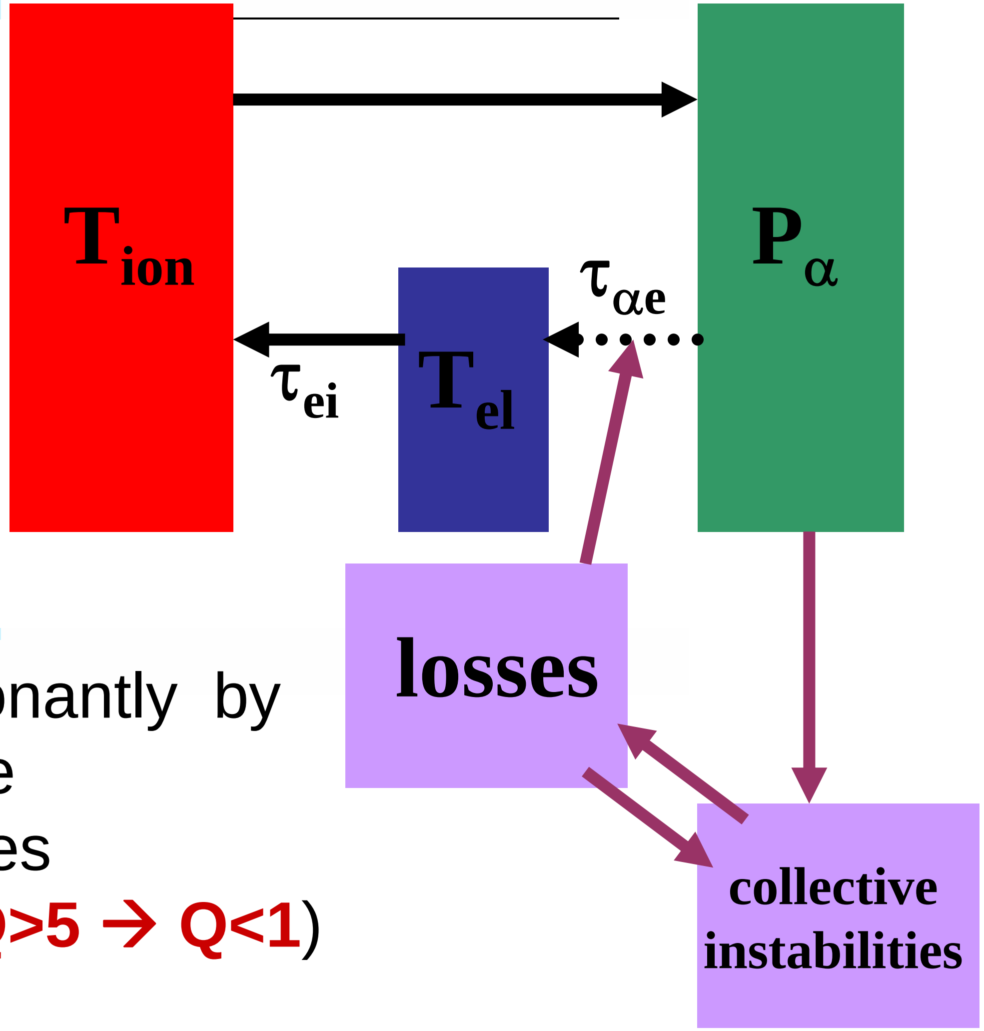




- **if α's are confined** and in the **absence of instabilities**, α's give all of their energy to electrons (as $T_e \sim T_i$ and $m_e << m_i$), which then heat ions via collisions to reach the temperatures for D-T fusion reaction to be sustained continuously
  - *fully demonstrated by JET D-T experiment with P_{FUS}=16MW, Q~0.7*

Effect of Collective Instabilities on the Self-Heating Process





if instabilities are excited resonantly by α's and reach large amplitude

➔ α's redistribution and losses

➔ reduction of fusion gain (**Q>5 → Q<1**)

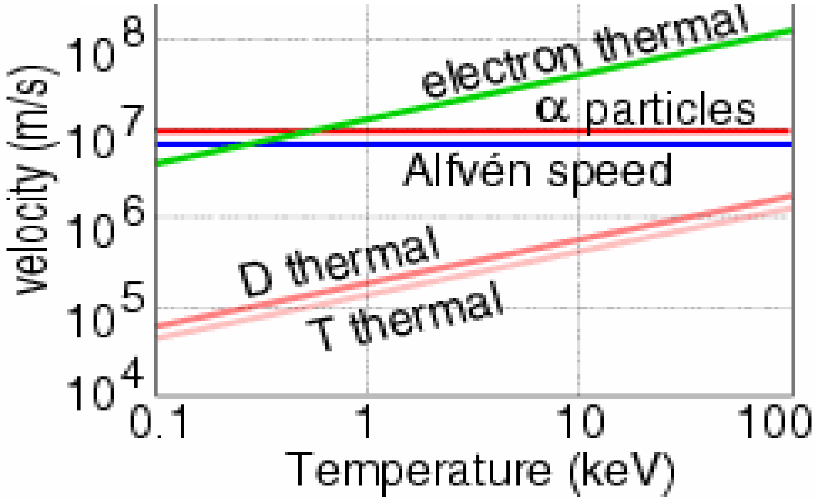
➔ potential for wall damage

what kind of collective instabilities resonate with α's?

Alfvén Waves and Eigenmodes

typical velocities in a tokamak

B=4T; n=10^{20}m^{-3}

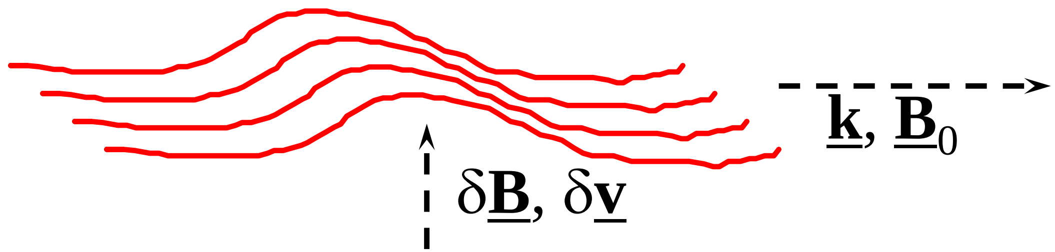


- α's resonate with Alfvén Waves
- AWs are driven unstable if

→ sufficient 'free' energy in α's

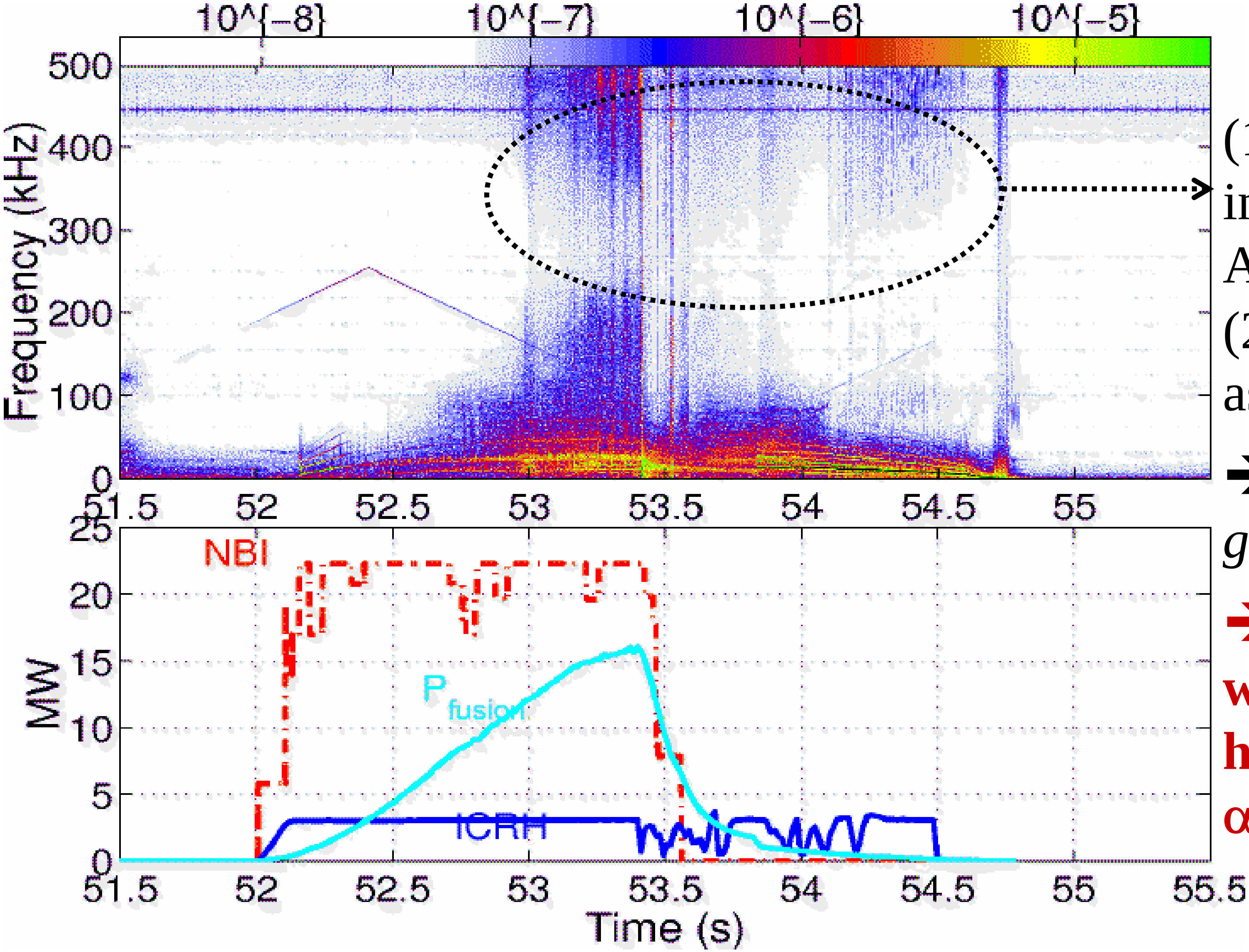
→ α's drive > plasma damping

- B-field and plasma frozen together; field lines are strings with tension and inertia → Alfvén wave propagation



- **in tokamaks: weakly damped Alfvén Eigenmodes (AEs)**
- toroidal geometry: different toroidal (n) and poloidal (m) harmonics (***≡A&A frequencies***) can be (and usually are) simultaneously excited

No α-driven Modes in Record Fusion Power Discharge (Q~0.7, P_f=16MW)



(1) no MHD instabilities in AE range

(2) α's behave as predicted

➔ *so far so good in JET ...*

➔ in ITER: what could happen to the α's at Q>5?

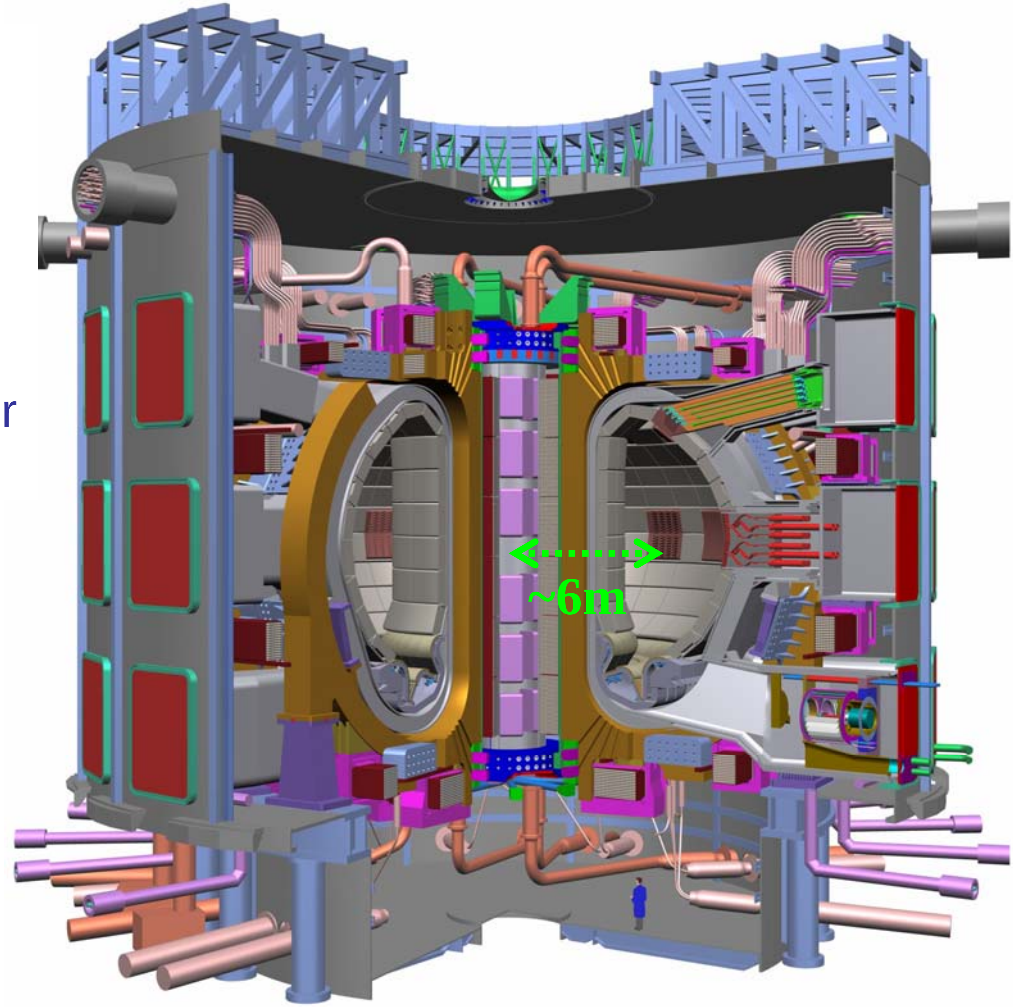
ITER: the Road Ahead
the World Burning Plasma Experiment

our goal: ***"to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes"***

- the role of ITER
  - burning plasma physics: $P_{fusion} \geq 500$MW for ~500s with $Q \geq 10$, $f_{\alpha} \geq 67\%$
  - integration of physics and technology
  - demonstrate and test fusion power plant technologies and safety

R~6.2m; B_T~5.3T; I_p~15MA

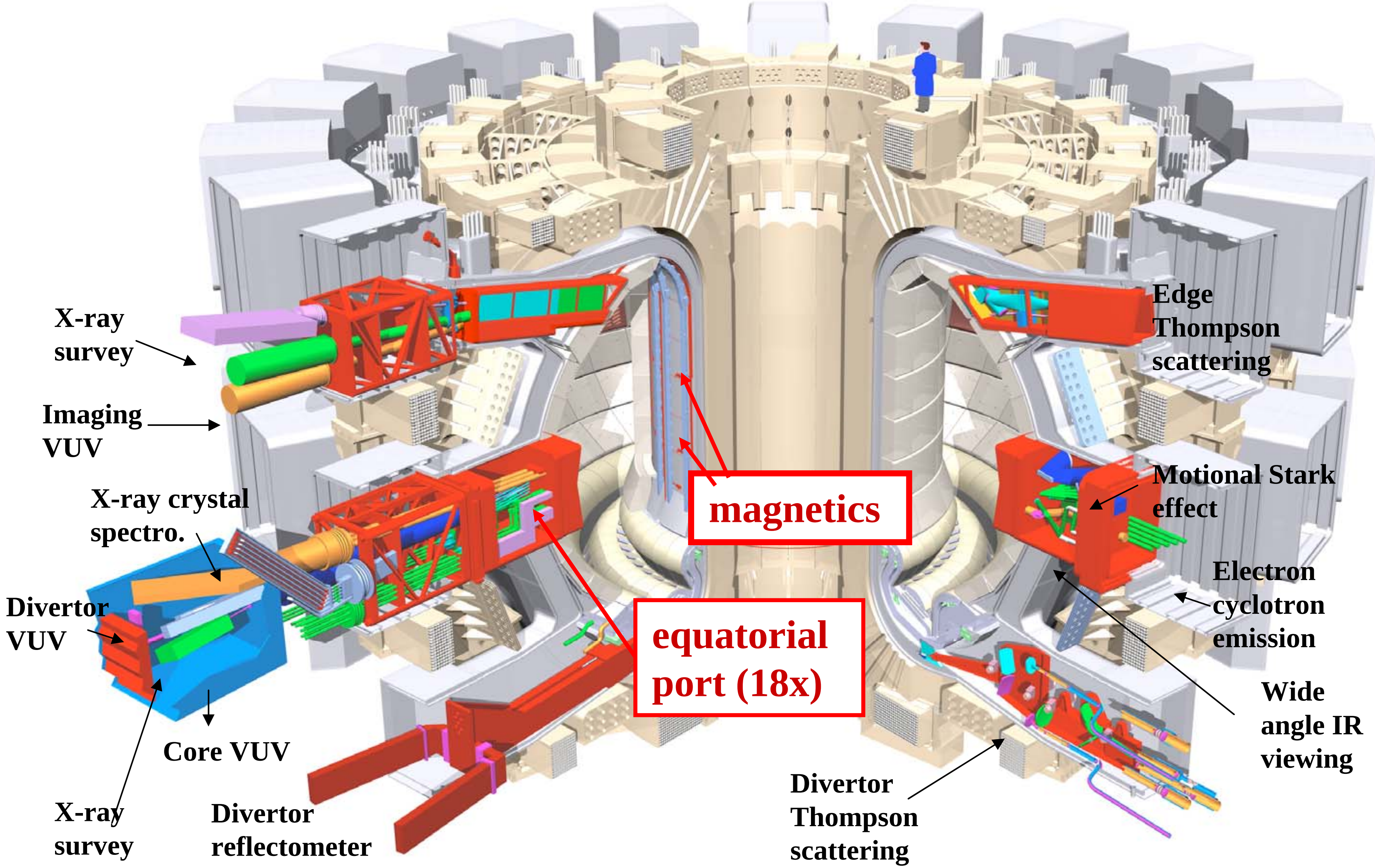
Fusion Power: 500MW
Plasma Volume: 840m^3
Nominal Plasma Current: 15MA
Typical Temperature: 20keV
Typical Density: 10^{20}m^{-3}
Pulse Length >1'000sec



ITER Diagnostics Systems

note: diagnostic are out-sourced, i.e.: built by associated labs and industries

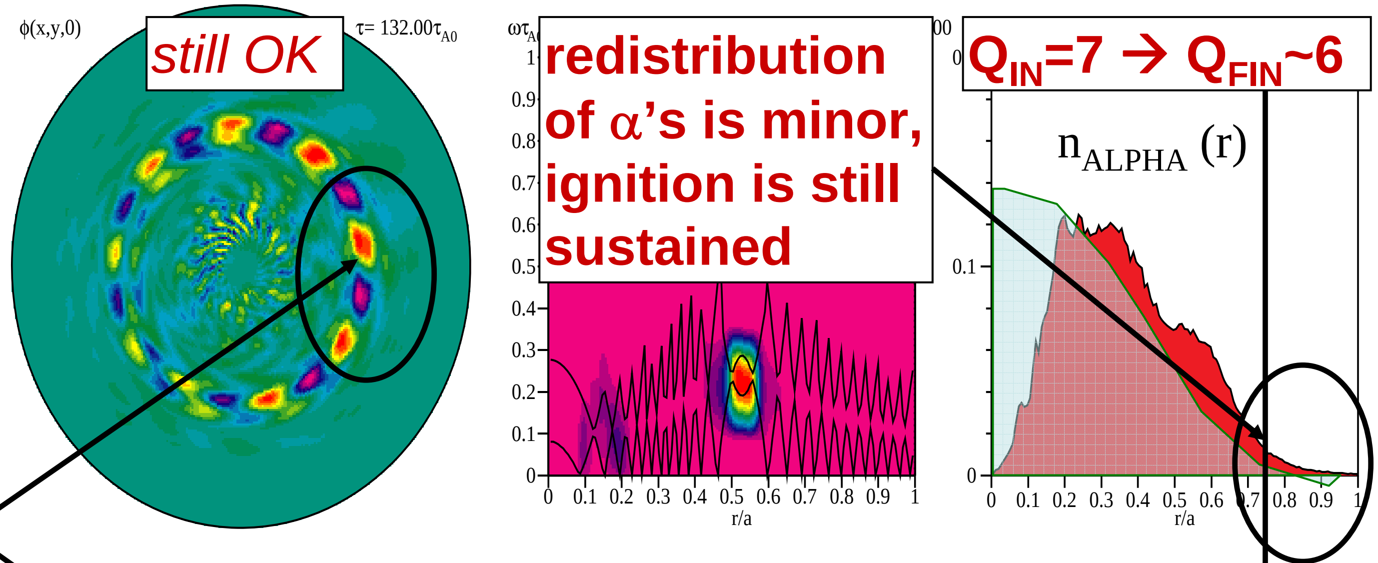
CRPP is in charge of R&D tasks for ITER magnetics, working with CEA (FR), ENEA (IT), CIEMAT (ES), ...

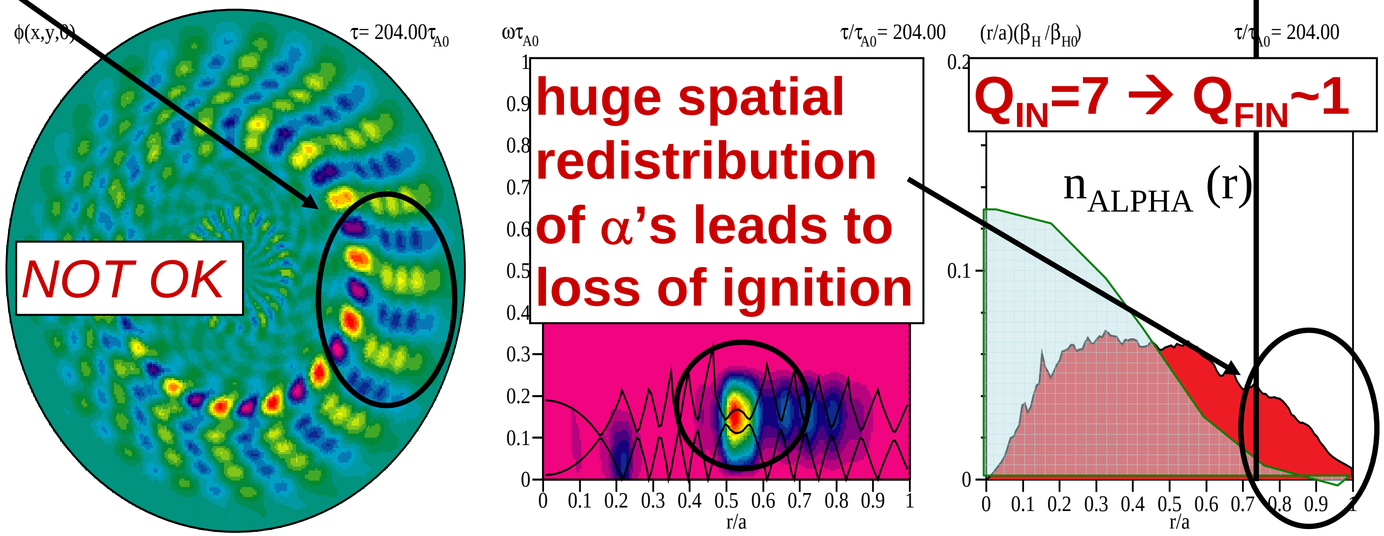


New Regimes for AE Interaction with α's Expected in Burning Plasmas (Q>5)

test simulation:
single n=6/m=10
mode interacting
with α's (in ITER)

need for real-time detection of dangerous MHD modes for active feedback control
➔ real-time control details depends on specific (n,m)

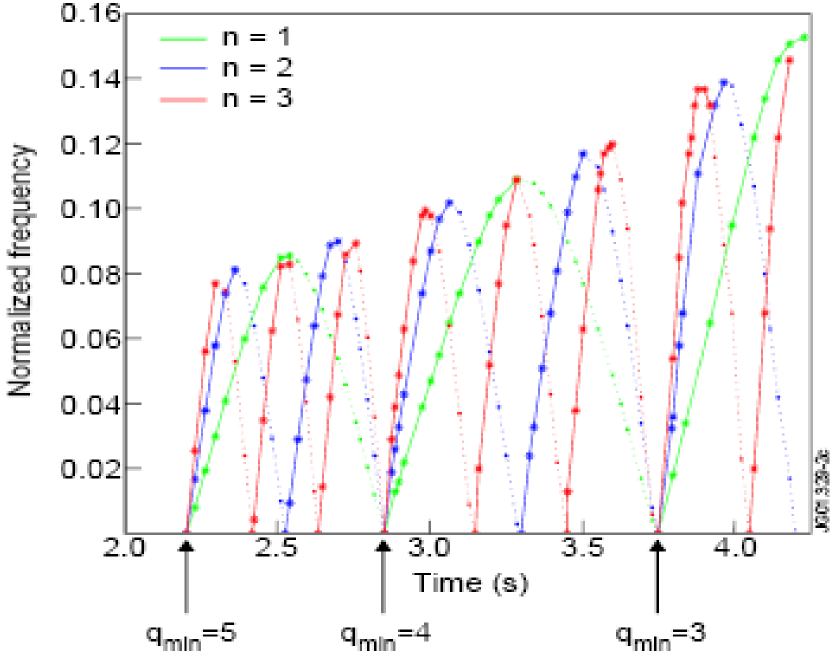




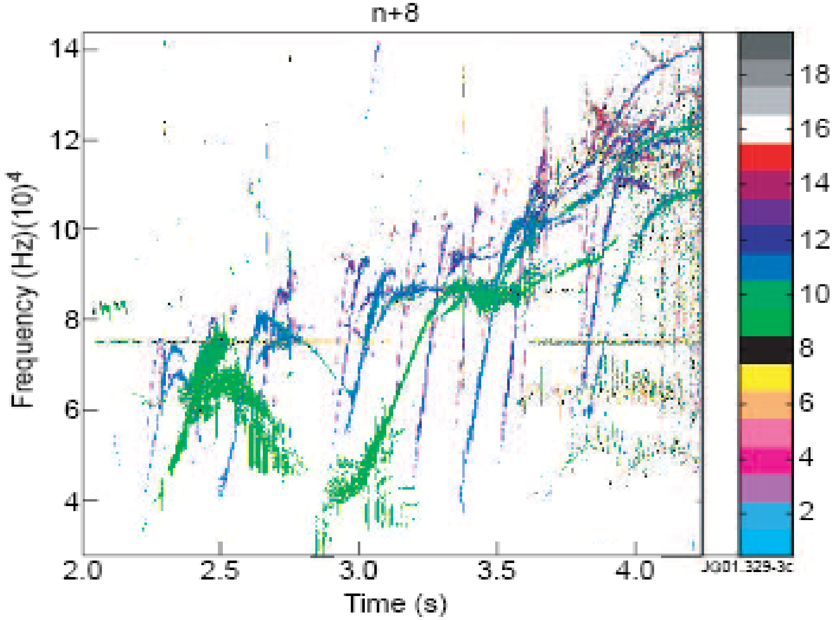
test simulation:
multiple n=5-10
modes interacting
with α's (in ITER)

Active MHD Spectroscopy for Plasma Diagnostic Relies on Precise Determination of Mode Numbers

Alfvén Cascades in JET plasma with non-monotonic current profile: we must control current profile to achieve good confinement of α's!



Time evolution n=1, n=2, and n=3 continuum tips during $q_{min}(t)$ evolution



Magnetic spectrogram showing Alfven Cascade Eigenmodes in reversed-shear JET plasma (pulse #49382)

Alfvén Cascades are routinely used in JET for diagnosing the current profile evolution

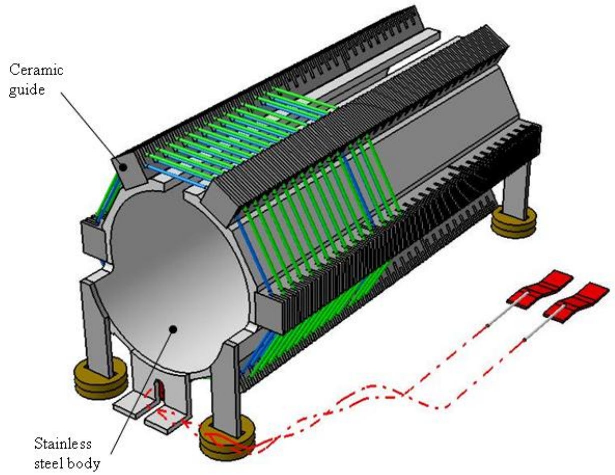
➔ **potential for real time application in JET and ITER, improvements of τ_E**

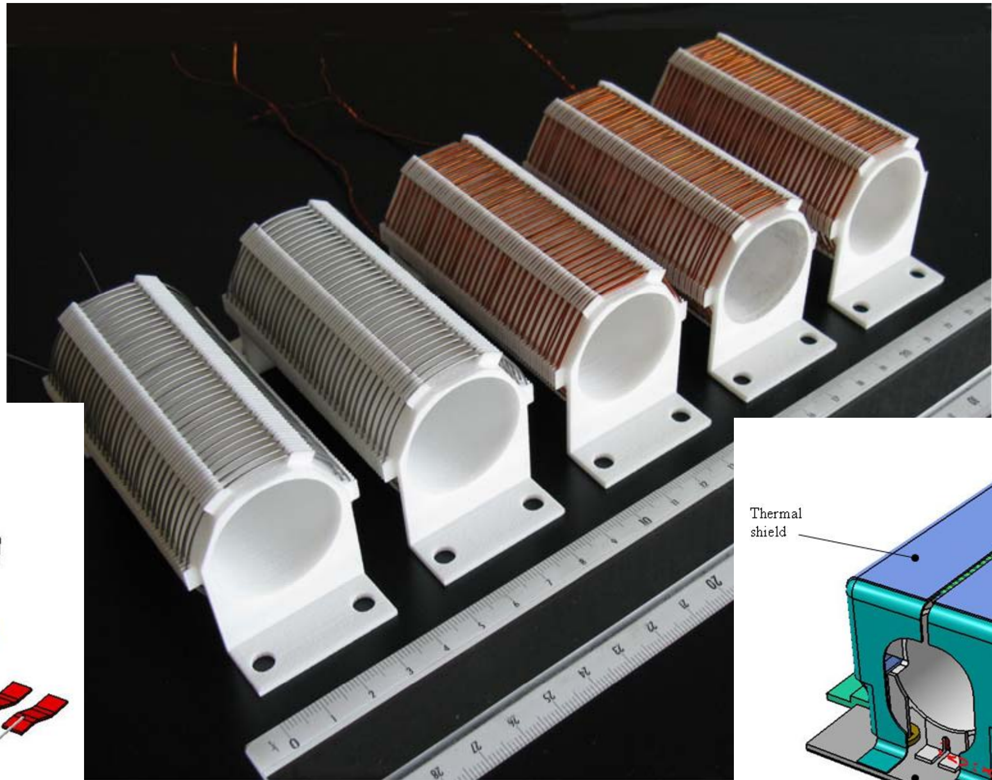
How Will ITER Measure the Spectrum of MHD Instabilities?

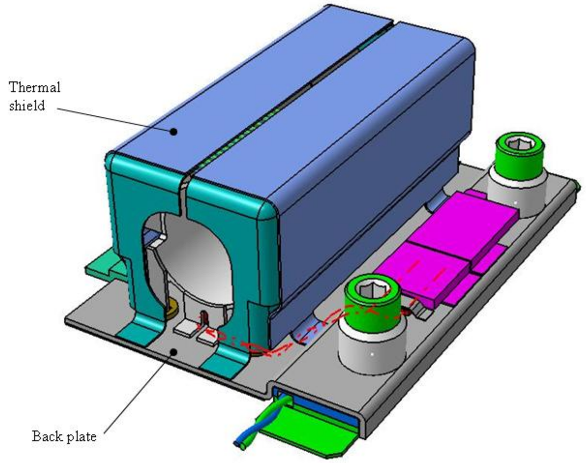
- ITER measurement requirements: detect modes with $|n| \leq 30$, $|m| \leq 50$, $|\delta B| \sim 10^{-4}$G
  - acceptable error on $|\delta B|$ ➔ ±15%
  - acceptable error on (n,m) ➔ ±0 for $(|n|,|m|)<5$, ±1 for $6\leq(|n|,|m|)\leq15$, ±2 for $16\leq(|n|,|m|)\leq25$, ±3 for $(|n|,|m|)>25$
- toroidal mode number detection: 2 arrays of 2x18 sub-assemblies with equi-spaced sensors on the low-field side
- poloidal mode number detection: 6 arrays of 16 un-evenly spaced sensors (with 50deg/360deg hidden periodicity)
- ***can add high-resolution arrays inside the equatorial ports***
- **we have envisaged and tested on simulated ITER data 6 further alternative geometries**
  - some examples of these analyses are presented here

The ITER Prototype Mirnov Coil

- hollow hexagonal ceramic body
- winding pack wound around the grooving in the ceramic support
- individual spacers mounted onto a stainless steel core
- 2 layers of 33 turns each to achieve a sufficient effective area $(NA)_{EFF}=0.05\text{-}0.1m^2$
- Mirnov coils fixed on a supporting metal plate (the “back” plate) to allow thermal and electrical contact with the ITER vacuum vessel







Challenges for the Measurement and Analysis of MHD Instabilities in ITER

- **multiple degenerate modes** expected at nearly the same frequencies
- **need precise ±1 determination** of toroidal and poloidal mode numbers for active feedback control and MHD spectroscopy in real-time
- **real-time applications** require <1ms clock-rate
- **uneven spatial sampling must be applied**
  - spatial Nyquist numbers cannot be achieved due to installation constraints
  - to measure $|n|=30$ ITER will need 60 sensors on each array
  - to measure $|m|=50$ ITER will need 100 sensors on each array
- **must conserve phase relation between I/Q components of measured fluctuation spectrum**
  - stable vs. unstable instabilities, damping and growth rate
- **blind analysis**, no previous knowledge of fluctuation spectra can be used
- **situation further complicated by the need for redundancy and resilience to the loss of sensors**
  - no easy access to inside of the vessel to replace faulty sensors
  - therefore "*risk management plan*" over the entire life of ITER (>30 years)

Traditional «Tokamak Fusion» Tools for Mode Number Analysis

- **straight line phase fitting**: cannot cope with multiple degenerate modes appearing at almost the same frequency
- **spatial Fourier decomposition**: requires uniform sampling up to the Nyquist number
- **Wigner and Choi-Williams distributions**: do not conserve phase relation between in-phase and quadrature signals (I/Q) in the complex δB measured by magnetic sensors
- **Lomb Periodogram**: cannot cope with multiple degenerate modes at the same frequency
- **wavelets and Singular Value Decomposition**: truly blind analysis requires too much CPU-time as ortho-normal basis are not known in advance
  - *these methods are suitable for post-pulse analysis*
  - *these methods are not suitable for real-time applications*

Analysis Methods from Astronomy and Astrophysics Help Tokamak Fusion

- finding periodic waveforms in un-evenly sampled data is an ubiquitous problem in the field of astronomy
  - temporal frequencies in astronomical data correspond to spatial mode numbers in fusion plasmas
  - un-evenly sampled data in time domain are the analog of data from un-evenly distributed Mirnov sensors in the toroidal and poloidal coordinates
- however there are some differences:
  - in astronomy: the frequencies sought are allowed to take any value
  - in tokamaks: periodic boundaries ensure that only modes with integer mode numbers (≡ integer frequencies in A&A) can exist
- a new method for fitting sinusoids to irregularly sampled data has been recently proposed, based on the principle of sparse representation of signals: the SparSpec code
  - freely available at: http://www.ast.obs-mip.fr/softwares

the Sparse Representation Method: SparSpec* Post-Pulse and Real-Time

- finding the solution with the sparsest spectrum on a **discrete (integer ≡ n!) frequency grid** using the minimization criterium:

$$\boxed{J(x) = \frac{1}{2}\left\|\mathbf{y} - W\mathbf{x}\right\|^2 + \lambda \sum_{k=-K}^{K} \left|x_k\right|_{L1}}$$

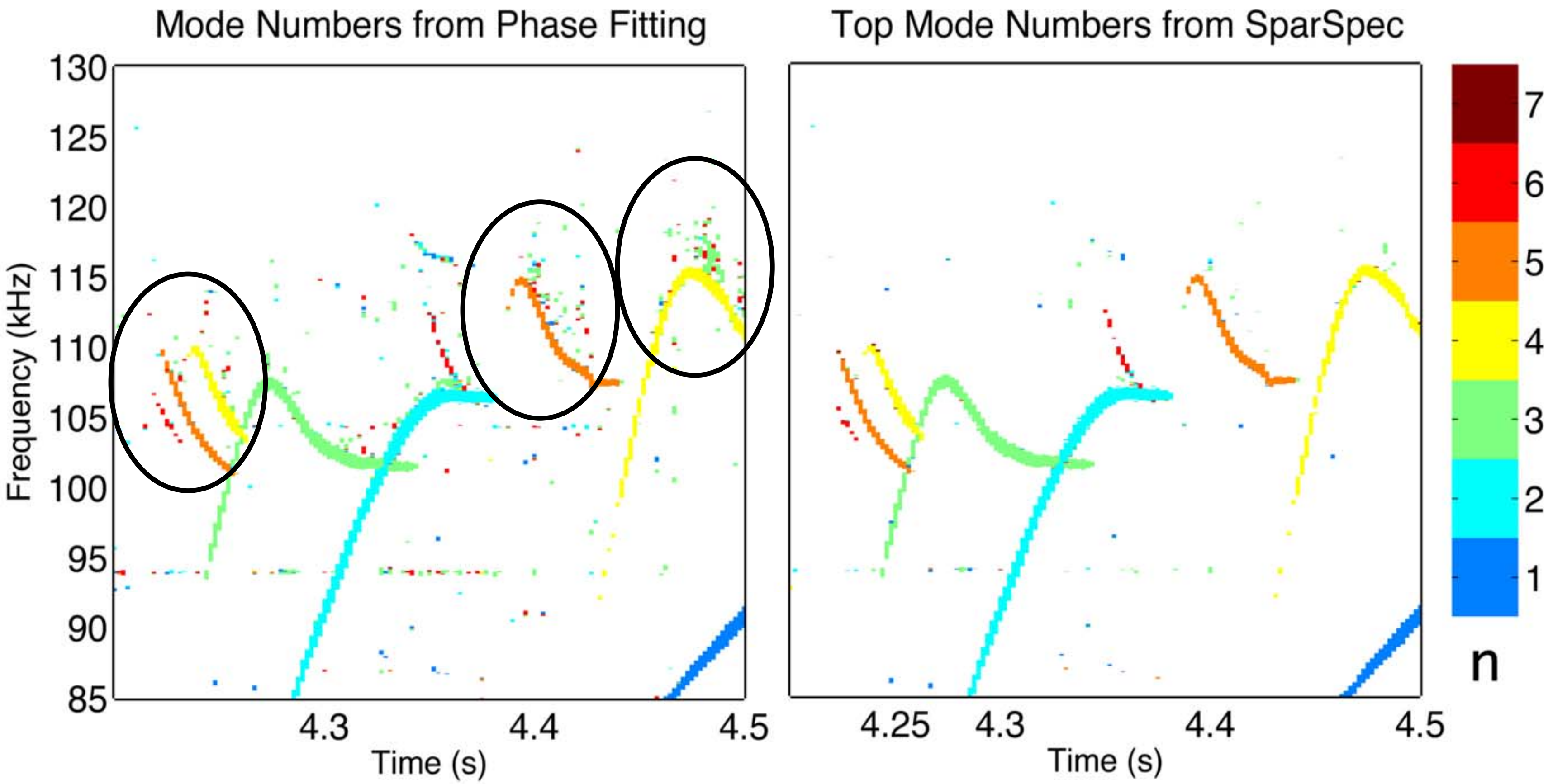
y: vector of data taken at time t_k [≡ position ϕ_k]
W: spectral window $\exp(i2\pi t_k f_n)$ [≡ $\exp(i2\pi\phi_k n)$]
x: vector of (I,Q) signals for with frequencies f_n
λ: parameter fixed to obtain a satisfactory sparse solution ➔ penalty criterion for invoking more modes to find adequate solution ($\lambda \leq \lambda_{MAX}$)
$\lambda_{\mathbf{MAX}}$: max(abs(W'*y)), fixed for known noise σ

- ideally suited for mode number analysis in fusion plasmas
  - allowable mode numbers are discretized: |n| = 1,2,3…
  - uses all information (time history from FFT, amplitudes, phases)
  - specifically suited for un-evenly distribution of sensors
  - very efficient, very fast convergence ➔ ideal for real-time applications
  - no restriction on n-range, number of modes not assumed a priori
  - **now implemented in JET real-time mode tracking algorithm**
    - already tested and working, some further optimization still needed

* S.Bourguignon, H.Carfantan, T.Böhm, Astronomy and Astrophysics **462** (2007) 379: **"SparSpec: A New Method for fitting multiple sinusoids with irregularly sampled data",** http://www.ast.obs-mip.fr/softwares

Toroidal Mode Number Analysis Using SparSpec Demonstrates its Superiority

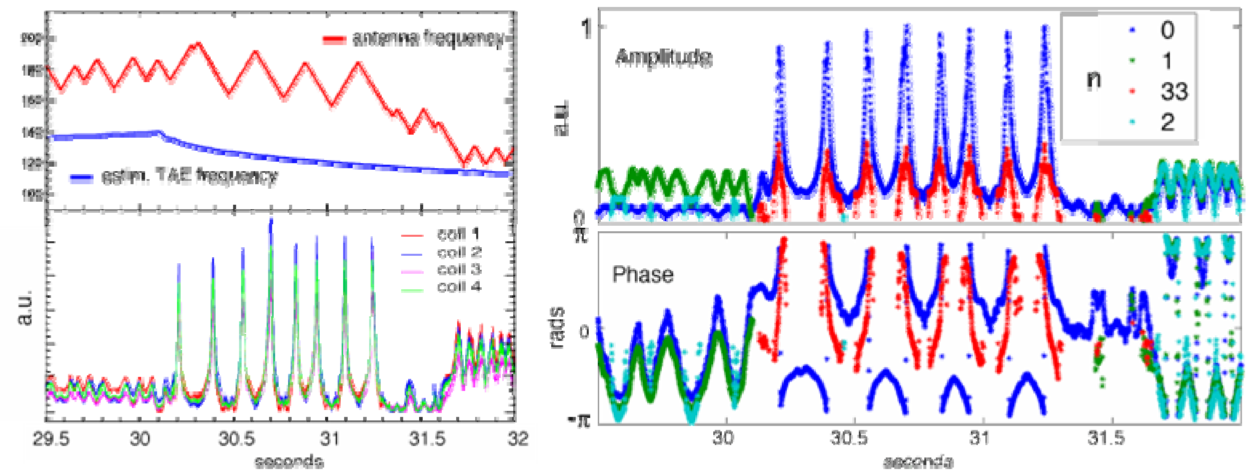
- calculation completed in <2min of CPU time with SparSpec
  - required >25min with SVDs, >10min with linear phase fitting
- **errors with linear phase fitting would have caused 10% underestimation of current in the plasma core, hence erroneous feedback re-action, if used for real-time control**



toroidal mode spectrum analysis in JET shot #69436 using eight Mirnov coils.
left: result obtained with least squares fit of phases to model of single mode; right: result obtained with SparSpec.

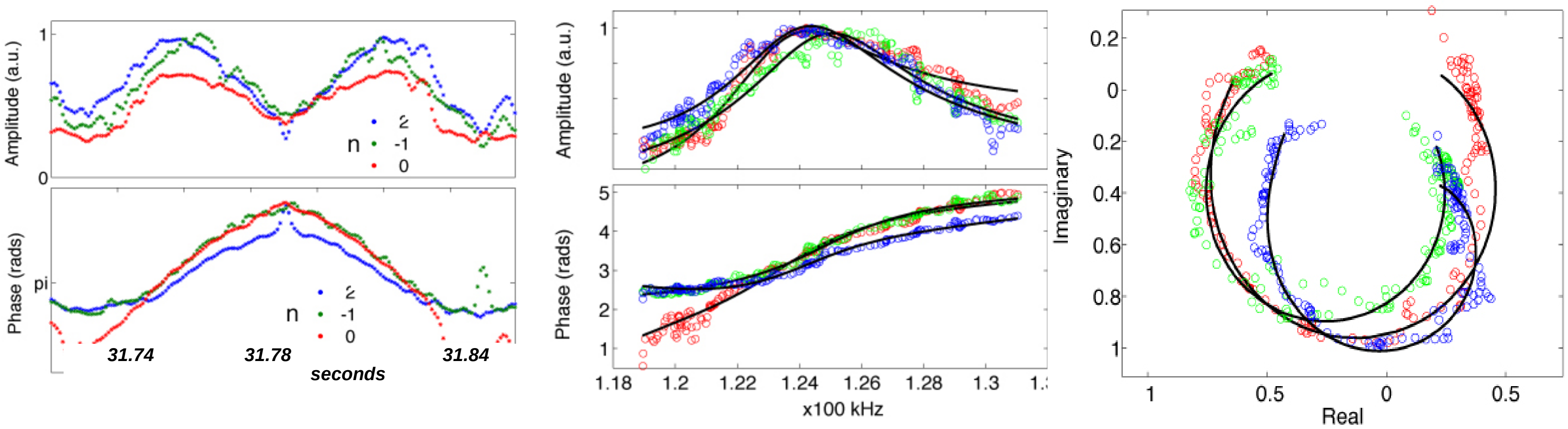
AE damping rates using SparSpec

- independent TAEs with different n
- **mode stability is a function of the n**
- with SparSpec: possible to get separate damping rate measurements for different n’s found at same time



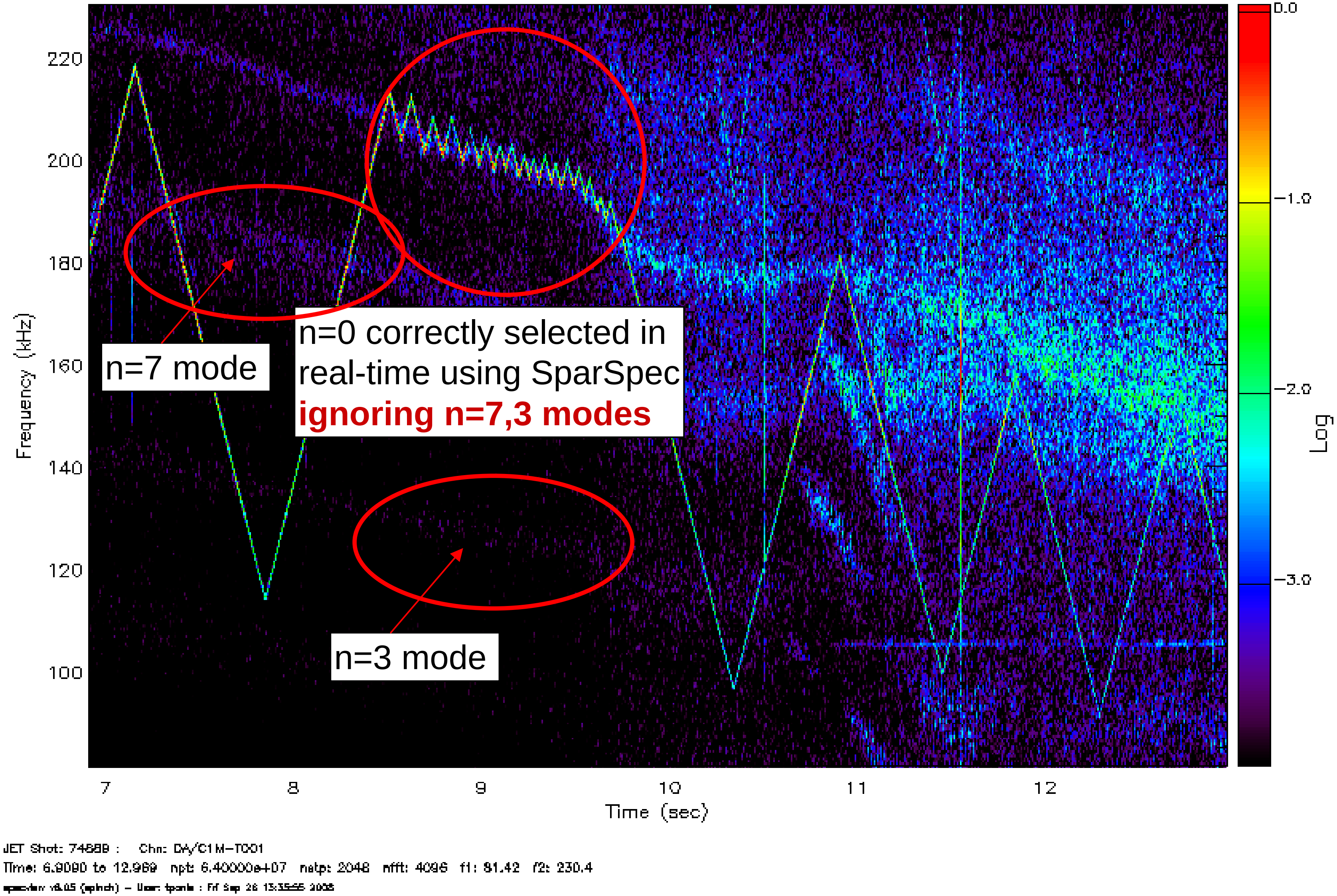
KC1T: TAE tracking during shot #69586➔ near t=32sec (right edge of window), three modes seen to be competing with almost equal amplitudes

damping rate obtained separately for the three modes (n=0,1,2)



Real-Time Mode Tracking via SparSpec

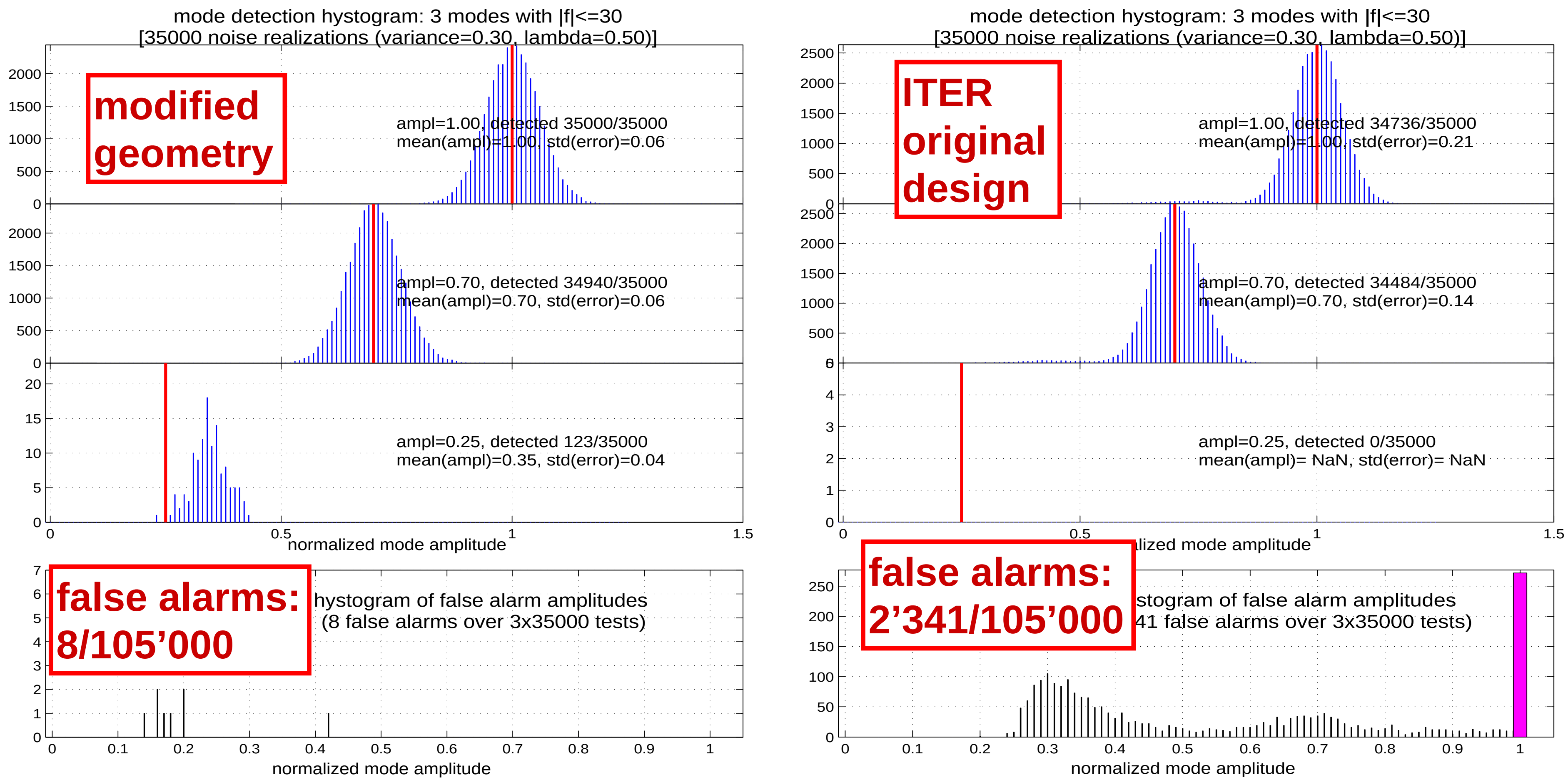
- **real-time identification and tracking of specific mode number using algorithm based on SparSpec code, with 1ms clock-rate (<600μs CPU)**



the Sparse Representation Method: from JET to ITER

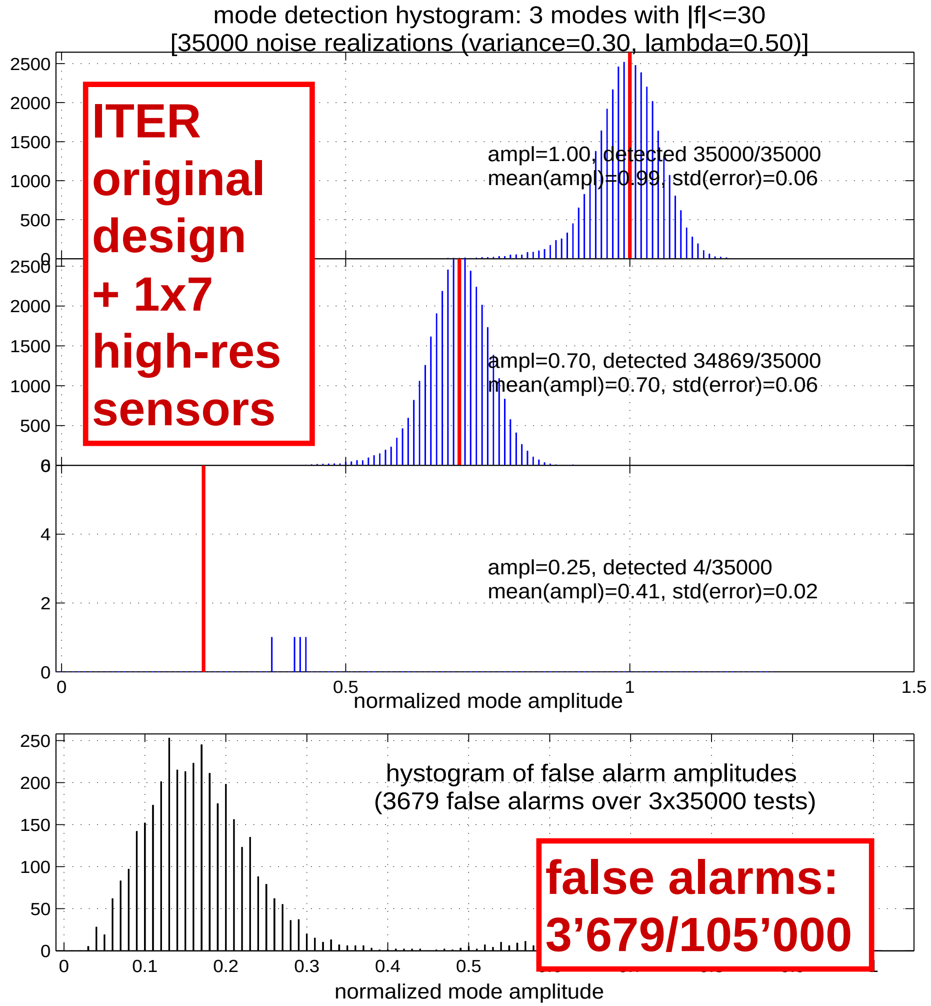
- the Sparse Representation algorithm is ideally suited for the baseline design and system optimization of the ITER high-frequency magnetics diagnostic because:
  - **it deconvolves correctly a degenerate input spectrum of modes**
    - specifically suited for un-evenly distribution of sensors
    - very efficient, with very fast convergence, ideal for real-time applications
    - no restriction on range of mode numbers and number of modes
  - **iterative changes of the spacing between sensors allows optimization of the spectral window for integer frequencies**
    - clear and universal criterion for system optimization
- **particularly suited to detect false alarms: modes that are not in the input spectrum that will trigger a control reaction to save the plasma**
- **particularly suited to infer importance of missing sensors, i.e. the resilience against the loss of faulty sensors**

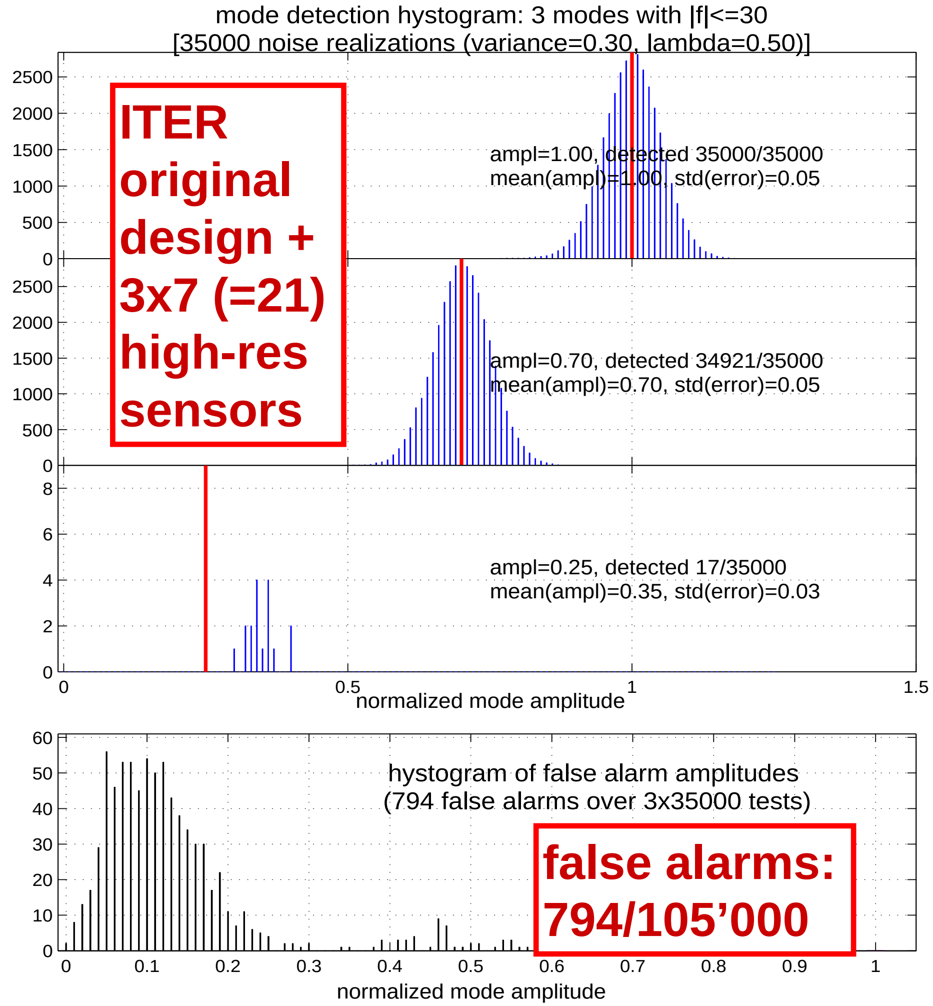
SparSpec on Simulated ITER Data: Statistics of False Alarms for n's



- **false alarms: modes have been detected which are not in the input spectrum**
- **note the very low number of false alarms for the modified ITER geometry: either the modes are correctly detected, or are not detected at all using un-evenly spaced sensors**

SparSpec on Simulated ITER Data: Statistics of False Alarms for n's





not even by adding 21 high-resolution sensors the ITER original design is sufficiently improved because of its 2x18 ➔ 9-fold Nyquist periodicity (ITER-V2: 8/105'000 false alarms)

SparSpec on Simulated ITER Data: Statistics of False Alarms for m's

- statistical analysis on calculation of poloidal mode numbers:
  - ITER-V1 (equi-spaced sensors) vs. ITER-V2 (randomly spaced sensors) vs. ITER-V8 (original system design, some hidden periodicities)
  - adding one high-resolution array in the equatorial port

NN	NHR	NP	False Alarms ITER-V1 *1st mod.*	Detected OK ITER-V1 *1st mod.*	False Alarms ITER-V2 *2nd mod.*	Detected OK ITER-V2 *2nd mod.*	False Alarms ITER-V8 *original*	Detected OK ITER-V8 *original*
16	**0**	**[0]**	**0.67**	**0.33**	**0.21**	**0.79**	**0.25**	**0.75**
16	3	[10]	0.58	0.42	0.18	0.82	0.22	0.78
16	5	[10]	0.49	0.51	0.13	0.87	0.17	0.83
16	**7**	**[10]**	**0.45**	**0.55**	**0.10**	**0.90**	**0.15**	**0.85**
16	10	[10]	0.52	0.48	0.12	0.88	0.21	0.79
16	12	[10]	0.55	0.45	0.18	0.82	0.29	0.71

- **equi-spaced geometry ITER-V1 has un-acceptably high number of false alarms**
- **truly random geometry ITER-V2 performs better that original ITER-V8**
- **addition of high resolution sensors beneficial provided not too closely spaced**

SparSpec on Simulated ITER Data: Resilience to the Loss of Sensors

Vgeo	Nsens [NP]	FMAX	σ: noise variance	λ	modified ITER-V2 geometry: un-evenly spaced sensors
02	**36+0**	*0→50	0.0→0.3	0.5	**1st run for ITER-V2, no high resolution array → scatter=1.75, <threshold (=2) → geometry OK**
02	36+1x3 [10]	30→50	0.0→0.3	0.5	2nd run for ITER-V2, 1x3 high-resolution sensors → scatter=1.56, <threshold (=2) → geometry OK
02	36+1x5 [10]	30→50	0.0→0.3	0.5	3rd run for ITER-V2, 1x5 high-resolution sensors → scatter=1.47, <threshold (=2) → geometry OK
02	**36+1x7 [10]**	30→50	0.0→0.3	0.5	**4th run for ITER-V2, 1x7 high-resolution sensors → scatter=1.44, <threshold (=2) → geometry OK**
02	36+1x10 [10]	30→50	0.0→0.3	0.5	5th run for ITER-V2, 1x10 high-resolution sensors → scatter=1.78, <threshold (=2) → geometry OK
02	**36+1x12 [10]**	30→50	0.0→0.3	0.5	**6th run for ITER-V2, 1x12 high-resolution sensors → scatter=2.03, >threshold (=2) → not OK**
02	**36+3x5 [3,10,14]**	30→50	0.0→0.3	0.5	**7th run for ITER-V2, 3x5 high-resolution sensors → scatter=1.32, <threshold (=2) → geometry OK**
02	36+3x5 [6,10,12]	30→50	0.0→0.3	0.5	8th run for ITER-V2, 3x5 high-resolution sensors → scatter=1.44, <threshold (=2) → geometry OK
02	36+3x5 [9,10,11]	30→50	0.0→0.3	0.5	9th run for ITER-V2, 3x5 high-resolution sensors → scatter=1.55, <threshold (=2) → geometry OK

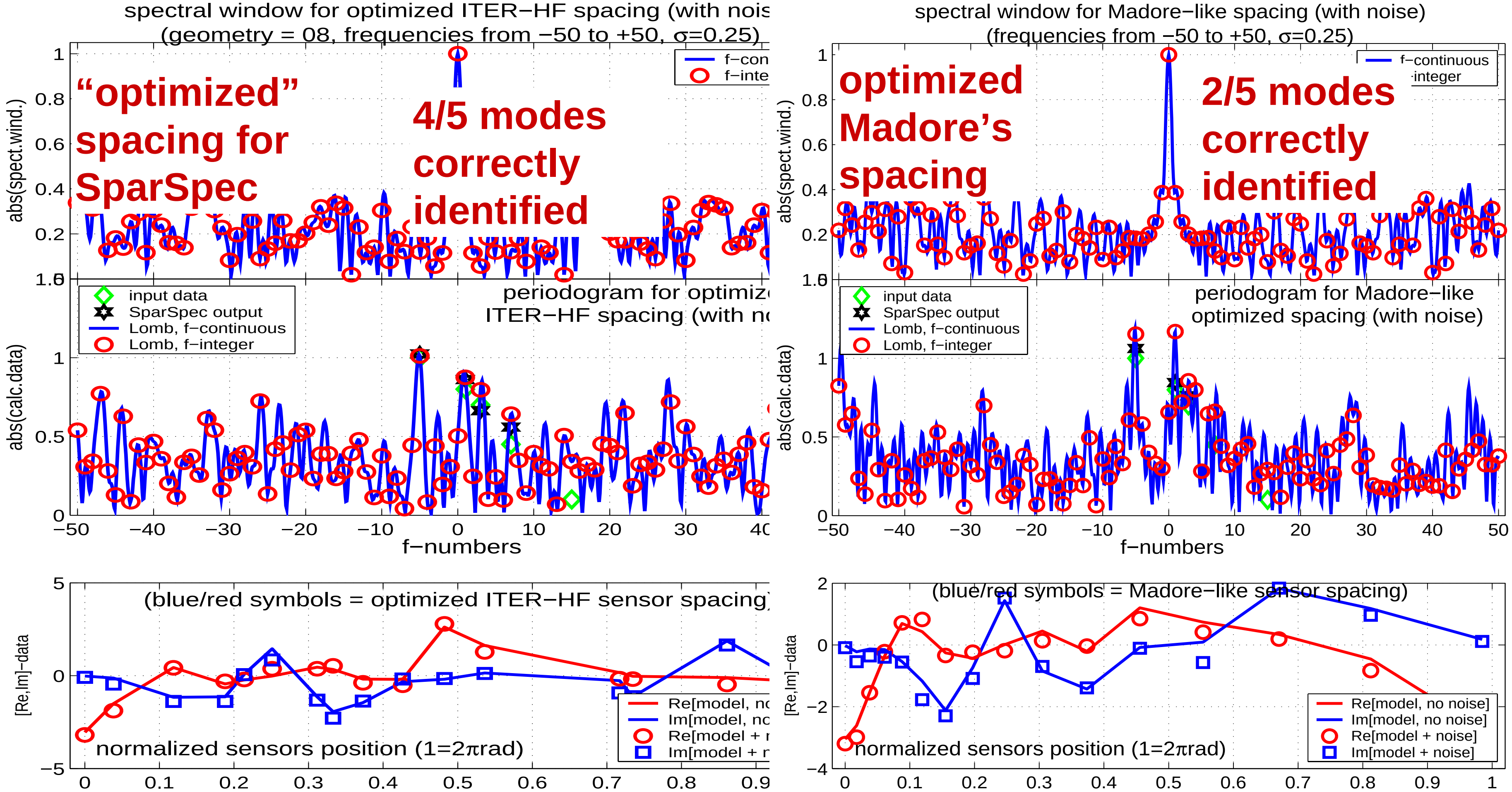
1. **ITER-V2 geometry with 36 un-evenly spaced sensors is very resilient to the loss of sensors**
2. **adding too many high-resolution sensors does not improve the situation**

SparSpec on Simulated ITER Data: Resilience to the Loss of Sensors

Vgeo	Nsens [NP]	FMAX	σ: noise variance	λ	nominal ITER geometry for n-number analysis
03	**36+0**	30→50	0.0→0.3	0.5	**1st run for ITER-V3, no high resolution array → scatter=4.25, >threshold (=2) → NOT OK**
03	36+1x3 [10]	30→50	0.0→0.3	0.5	2nd run for ITER-V3, 1x3 high-resolution sensors → scatter=2.68, >threshold (=2) → NOT OK
03	36+1x5 [10]	30→50	0.0→0.3	0.5	3rd run for ITER-V3, 1x5 high-resolution sensors → scatter=2.24, >threshold (=2) → NOT OK
03	**36+1x7 [10]**	30→50	0.0→0.3	0.5	**4th run for ITER-V3, 1x7 high-resolution sensors → scatter=2.19, >threshold (=2) → NOT OK**
03	36+1x10 [10]	30→50	0.0→0.3	0.5	5th run for ITER-V3, 1x10 high-resolution sensors → scatter=3.05, >threshold (=2) → NOT OK
03	36+1x12 [10]	30→50	0.0→0.3	0.5	6th run for ITER-V3, 1x12 high-resolution sensors → scatter=5.26, >threshold (=2) → NOT OK
03	**36+3x5 [3,10,14]**	30→50	0.0→0.3	0.5	**7th run for ITER-V3, 3x5 high-resolution sensors → scatter=1.85, <threshold (=2) → geometry OK**
03	36+3x5 [6,10,12]	30→50	0.0→0.3	0.5	8th run for ITER-V3, 3x5 high-resolution sensors → scatter=1.97, <threshold (=2) → geometry OK
03	36+3x5 [9,10,11]	30→50	0.0→0.3	0.5	9th run for ITER-V3, 3x5 high-resolution sensors → scatter=2.05, >threshold (=2) → NOT OK

1. **ITER-V1 geometry with 36 equi-spaced sensors is not at all resilient to the loss of sensors**
2. **adding 1x7 high-resolution sensors improves the situation but not enough**
3. **only adding 3x7=21 high-resolution sensors improves sufficiently the measurement performance**

SparSpec on Simulated ITER Data: Optimization of Sensor Spacing



1. spectral window for the optimized sensor spacing (left) and the Madore's one (right), using 5 input modes
2. allowing ±5deg shift in the sensors' position to optimize measurement performance
3. **only the lowest amplitude mode is not detected with the optimized ITER-V2 spacing, 16 sensors**
4. **just the top two modes are detected using Madore's spacing , 16 sensors**

Summary of Results on Optimization of ITER System Design for MHD Sensors

- sensor arrangements made of sub-assemblies with spatial periodicities are more prone to fault detection of high-n(m) modes
  - situation only marginally improved by adding high-resolution array(s) inside the equatorial port(s)
- un-evenly spaced sensors arrangements are the more robust against false detection of high-n(m) modes if the spatial coverage is sufficiently complete
  - adding high-resolution array(s) inside equatorial port(s) does not improve significantly the system performance
- if the spatial coverage leaves significantly large regions blacked-out, adding a small number of sensors in high-resolution arrays inside the equatorial ports does improve the resilience against false detection of high-n(m) modes
- the best use of high resolution arrays inside equatorial ports is to have a relatively low number of sensors (5 to 7) in ports which are as far apart as possible

Summary of Results on Optimization of ITER System Design for MHD Sensors

- **the analysis of the baseline system design demonstrates that the nominal implementation of the magnetic sensors for MHD analysis does not satisfy the measurement requirements for toroidal and poloidal mode number analysis in ITER**
  - toroidal mode number analysis: spatial symmetries in sensor geometry giving intrinsic Nyquist number: n=9
  - poloidal mode numbers: not enough sensors, non-optimized spatial coverage, large regions blacked-out
- **design optimized geometry for ITER magnetic sensors for MHD analysis by minimizing the maximum of spectral window for integer frequencies**
  - coherently with algorithm of Sparse Representation of signals
  - analysis done, optimized “ideal” geometry has been determined

Ideal Optimized Geometry for Magnetic Sensors in ITER

- outline design for the ITER HF sensor system for toroidal mode number analysis can be developed so as to have:
  a) on the low field side, 2 arrays at the Z-height of each horizontal side of the equatorial port, each array made of 20 un-evenly spaced sensors plus 6x5 high resolution arrays located in each one of the equatorial ports used by the poloidal HF sensor system
  b) on both the low- and high-field sides, 2 further arrays of 25-30 un-evenly spaced sensors located approximately between 45cm and 70cm above and below the Z-centre of each equatorial port
- outline design for the ITER HF sensor system for poloidal mode number analysis can be developed so as to have:
  c) one array of 20-25 un-evenly spaced plus 5-7 high resolution sensors replicated in six non equi-distant machine sectors, not covering the divertor region and poloidal angles $80<|\theta|(\mathrm{deg})<90$
- very large redundancy in the n- and m-number measurements
- a total of 2x(20+30) (a) + 4x(25-30) (b) + 6x(25-30) (c)

➔ **350-400 sensors for high frequency MHD analysis in ITER**

- **with this: ITER risk management plan guidelines fully satisfied**

Needs for Future Work for ITER

- **use SparSpec to “design” optimized geometry for ITER magnetic sensors for MHD analysis by minimizing the maximum of spectral window for integer frequencies**
  - analysis done, optimized “ideal” geometry has been determined
  - **ITER will install more sensors than actually needed**

our work is not yet completed (mine, CRPP, ITER, ...):

- need to integrate engineering and installation constraints with need for redundancy and risk management
- how do we decide how many more sensors we need to install?
- how do we decide on the replacement of faulty sensors?
- and which subset of these should we use for the actual data analysis?
- how can we ensure uniqueness of the results of the analysis when using a subset of the available sensors?
- how can we implement this analysis reliably for real-time applications?
- how can we CLEAN the input spectrum (remove too short wavelengths)?
- *can we bring together techniques from astronomy and astrophysics into tokamak fusion plasmas for the design of the ITER magnetic diagnostics?*

can you help me??

thank you for your attention!